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EXPERIMENTAL INVESTIGATION OF AIR FILM COOLING
APPLIED TO AN ADIABATIC WALL BY MEANS OF AN
AXIALLY DISCHARGING SLOT

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EXPERIMENTAL INVESTIGATION OF AIR FILM COOLING APPLIED TO AN ADIABATIC WALL BY MEANS OF AN AXIALLY DISCHARGING SLOT

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SUMMARY

An experimental investigation was made to determine the characteristics of axially discharging single-slot film cooling of an adiabatic wall exposed to a hot-air stream. Mainstream gas temperature ranged from 520° to 2000° R and the mainstream Mach number was varied from 0.15 to 0.70. Cooling-air temperatures ranged from 540° to 870° R and the cooling-air Mach number was varied from 0.0 to 1.0. Basic film-cooling-data plots for the four slot heights investigated (1/2, 1/4, 1/8, and 1/16 in.) have been presented in nondimensional form.

In order to obtain a data correlation covering the range of effective temperature ratios from 0.1 to 1.0, it was necessary to use four variations of a basic correlating equation. The four equations and their limitations have been included.

Within well defined restrictions, an evaluation of the data showed a temperature-ratio effect on the effective temperature parameter. The square root of this temperature ratio (T_a/T_g) was introduced into the data correlation where applicable.

INTRODUCTION

A surface exposed to a high-temperature gas stream can be protected by injecting a layer of cooler gas along the surface in such a manner as to form an insulating blanket between the hot gas and the surface to be cooled. This method is called film cooling even though the film remains an entity only for a short distance downstream of the injection point.

The complexity of the mechanism involved in the interaction of the hot and cold streams makes it difficult to calculate film-cooling performance on a strictly theoretical basis. In several investigations (refs. 1, 2, and 3) attempts were made to do this by the use of simplifying assumptions. Experimental investigations were carried out in references 1, 4, and 5. The use of semiempirical means made it possible to obtain film-cooling correlating equations based on data subject to respective rig limitations. Unfortunately, the range of variables examined was quite limited.

In reference 4 an adiabatic flat plate exposed to a cold (492° R) airstream was heated by discharging hot air through a slot at the surface of the plate. The velocity of the cold airstream was varied from 52 to 105 feet per second. The temperature of the injected air ranged from approximately 542° to 571° R. The correlating parameters in reference 4 were the effective temperature ratio $[(T_g - T_w)/(T_g - T_a)]$, specific weight flow ratio $[(\rho V)_a/(\rho V)_g]$, and the distance ratio x/s.

The same type of setup was used in references 3 and 4, but in reference 4 instrumentation was employed to evaluate heat-transfer coefficients. Furthermore, use of two basic slot configurations, which included normal and parallel injection of the coolant relative to the test plate, demonstrated the film-cooling superiority of the parallel slot discharging axially downstream. Mainstream gas temperature ranged from 515° to 520° R and mainstream velocity was varied from 42 to 123 feet per second. The temperature of the injected air ranged from 565° to 655° R.

The experimental investigation of reference 1 dealt primarily with normal injection of the coolant, and again the range of primary variables examined was quite limited.

In order to evaluate further the usefulness and limitations of film cooling, an experimental investigation was undertaken at the NASA Lewis Research Center to extend the range of variables previously investigated and to attempt a correlation using basic parameters applicable for design information.

Film cooling was evaluated herein using single slots discharging the coolant downstream and parallel to the test plate. Fine screens and well rounded approach sections were used in both the hot and cold streams to minimize turbulence effects. The test section was an 8- by 8-inch rectangular duct 36 inches in length. The test plate was the insulated top wall of the test section. Mainstream gas temperature ranged from 530° to 2000° R and mainstream Mach number was varied from 0.15 to 0.7. The cooling-air temperature was varied from 540° to 870° R and was discharged through slot heights of 1/2, 1/4, 1/8, and 1/16 inch. The specific weight flow ratio $[(\rho V)_a/(\rho V)_g]$ was varied from 0 to 13.9. Table I lists the number of runs showing the range of data obtained. Within this range the effect of radiation from the three uncooled walls of the test section was found to be negligible.

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Since no theoretical model was developed, it would not be reliable to extrapolate the data and correlations obtained in this investigation to (a) conditions outside the range of measurements, (b) conditions where radiation is important, (c) conditions of flow other than those existing in the test, or (d) other fluids than air.

SYMBOLS

A	flow area, sq in.
M	Mach number
P	absolute total pressure, lb/sq in.
p	absolute static pressure, lb/sq in.
s	slot height, in.
T	total temperature, $^{\circ}R$
V	velocity (gas), ft/sec
W	gas weight flow, lb/sec
x	distance on adiabatic wall measured from slot discharge position, in.
ρ	density, lb/cu ft
$\frac{(\rho V)_a}{(\rho V)_g}$	specific weight flow ratio
$\frac{T_g - T_w}{T_g - T_a}$	effective temperature ratio
x/s	distance ratio

Subscripts:

a	slot gas
g	mainstream gas
w	adiabatic wall, flat plate

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APPARATUS AND INSTRUMENTATION

Figure 1(a) is a photograph of the film-cooling rig taken prior to installation of the external insulation about the test section, and figure 1(b) is a schematic diagram of the complete test assembly showing instrument stations listed in table II. The can-type combustors discharged into a mixing section containing a system of baffles and screens designed to obtain uniform temperature and pressure profiles at station (1). Total-pressure rakes and static-pressure wall taps were installed at station (1) to measure mainstream gas flow. Additional screens downstream of station (1) were included to further obtain uniform flow conditions.

A can-type combustor was also installed in the cooling-air line in order to vary the temperature of the injected air. Cooling airflow was measured at station (3) by means of orifices sized to handle a wide range of airflow rates.

Cooling air entered the slot box (section (a)) and was tangentially ejected through the slot along the test plate (section (b)). Rounded approach sections in the slot box and fine screens in the cooling gas line were used to induce uniform flow conditions. Four readily exchangeable slot boxes were used with slot heights ranging from 1/16 to 1/2 inch. Table I lists the pertinent dimensions.

Figure 1(c) shows two photographic views of the test plate showing instrumentation fittings. The test plate was the 8- by 36-inch insulated top wall of the test section. It was made of 1/16-inch Inconel with thermocouples embedded close to the surface which is exposed to the hot gas. A mineral-type insulating material good up to 2500° F was used behind the test plate to prevent radial heat transfer. Table II(b) lists the distribution of the thermocouples and static-pressure taps along the test plate relative to the slot discharge position. All the instrumentation was installed within a 4-inch band along the plate centerline allowing 2 inches on either side in an attempt to eliminate fluid dynamic and heat-transfer effects caused by the side walls of the test section.

The test setup was supported on rollers to allow for axial thermal expansion, and the complete assembly was covered with insulation to minimize heat loss into the test cell. The assembly was connected to the laboratory air supply and discharged to ambient conditions.

The total temperature of the mainstream flow was measured in the plane of discharge of the slot (station 2) while the cooling-air temperature was measured in the slot box (section (a)).

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PROCEDURE

For each run a standard procedure was employed in which all variables were constant except the cooling-air weight flow. The mainstream gas temperature and Mach number were set at desired values and the amount of cooling air ejected through the slot was varied for each data point by progressive settings of the control valves. At each setting sufficient time was allowed in order to obtain equilibrium conditions before the necessary pressures and temperatures were recorded.

The same procedure was repeated at various mainstream Mach numbers and temperatures for the four slot heights investigated. For the majority of the runs the cooling air was used at the temperature supplied by the laboratory, but for some of the runs the air was heated within a limited range.

RESULTS AND DISCUSSION

Presentation of Data

Basic nondimensional data plots, showing the axial distribution of effective temperature ratio for various constant values of specific weight flow ratio for the four slot heights investigated (1/2, 1/4, 1/8, and 1/16 in.), are presented in figures 2 to 5, respectively. These plots include all data obtained during subject investigation and are presented in lieu of data tabulations.

Parametric Effects on Film Cooling

The interrelated parameters of the basic data plots were varied systematically to determine their effects on film cooling. Data showing these trends and effects are presented in figures 6 to 8. It should be emphasized that although these curves represent the general trends, they constitute a sampling only of the complete data of figures 2 to 5.

Slot-height effects. - Figure 6 is a plot of effective temperature ratio against the (x/s) parameter for the range of slot heights investigated (1/16 to 1/2 in.). Mainstream Mach number, temperature ratio (T_g/T_a), and specific weight flow ratio are held constant. Within these restrictions it is noteworthy that the conventional effective temperature ratio generalizes as a function of the (x/s) parameter.

Mainstream Mach number effects. - The effective temperature ratio is plotted against (x/s) for various mainstream Mach numbers on figure 7. For this plot the slot height, temperature ratio (T_g/T_a), and specific weight flow ratio are held constant. Over the range of Mach numbers investigated it can be observed that mainstream Mach number effects are quite small and within the accuracy of the data can be considered negligible.

Specific weight-flow-ratio effects. - The plots of basic data in figures 2 to 5 show the effect of varying the specific weight flow ratio on the effective temperature-ratio parameter. Figure 2(a) is a typical example showing the effective temperature ratio plotted against (x/s) for various values of specific weight flow ratio. In this case mainstream Mach number, slot height, and temperature ratio (T_g/T_a) were held constant.

An examination of the data shows that with increasing distance x downstream of the slot discharge position the constant specific weight-flow-ratio curves asymptotically approach some value of effective temperature ratio depending on the temperature of the gas mixture. The rate of effective temperature-ratio drop along a constant specific weight-flow-ratio curve depends on the change in heat and momentum exchange between the hot gas stream and the cooling film. It should be noted that, at the slot discharge position, the effective temperature ratio is influenced by heat transfer through the slot-box wall and by recirculation of the hot mainstream flow into the cooling slot which occurred at low values of specific weight flow ratio.

It can generally be observed that the effective temperature ratio varies with some function of specific weight flow ratio.

Temperature-ratio effect (T_g/T_a). - In figure 8 the effective temperature ratio is plotted against (x/s) for various values of (T_g/T_a) ratio. The mainstream Mach number, slot height, and specific weight flow ratio are held constant. A temperature-ratio effect is readily observed on this plot. Note that the trend of the effect of temperature ratio also holds for the inverted temperature-ratio curve $(T_g/T_a = 0.545)$ which simulates a film-heating problem.

Cooling-gas temperature-level effect. - The two sets of curves on figure 9 are plots of data obtained at two different cooling-air temperature levels. The abscissa for both sets is the (x/s) ratio but the ordinate for one is the effective temperature ratio $(T_g\text{-}T_w/T_g\text{-}T_a)$ while the ordinate for the other is the adiabatic wall temperature (T_w). In both cases the mainstream Mach number, slot height, and mainstream gas temperature are held constant while the individual curves on each plot are for different cooling-air temperatures.

The three plots of figure 9(a), (c), and (e) in the order of increasing specific weight flow ratio show the temperature-ratio effect

T_g/T_a previously introduced. Increasing the specific weight flow ratio also increases this effect. It may be noted that the higher-temperature cooling air appears to be more effective.

An examination of figures 9(b), (d), and (f) shows that at the slot discharge position a wall-temperature difference exists between the two different cooling-air temperature curves on each plot but that progressing downstream both curves approach each other quite rapidly and become equal at values of (x/s) depending on the specific weight flow ratio. Since the wall temperatures on each plot are essentially equal beyond a certain value of x/s, it can be observed that the use of lower-temperature cooling air does not necessarily mean obtaining better cooling.

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A possible explanation for this phenomenon is that the higher temperature cooling air produces more effective cooling due to the increased gas velocity supporting the cooling film.

Correlation of Results

An empirical correlation of data obtained at low temperatures and velocities by employing a parameter of the form $\left[\frac{x}{s}\Big/\frac{(\rho V)_a}{(\rho V)_g}\right]$ was developed in reference 4. Figure 10 is a plot showing fairly good agreement between data at (x/s) ratios greater than 100 (ref. 4) and the present data at an (x/s) value of 70. The comparison was made using the film-heating data obtained in this investigation because it is directly comparable to that of reference 4.

An approach similar to the one of reference 4 was used in attempting to correlate the present data. It was assumed that the form of the correlation would probably be more complicated since heat-transfer rates change and the difference in fluid properties starts to become significant at the temperatures employed in the present investigation. This complication might be related in some manner to the temperature levels of the two fluids.

Correlating procedure. - The attempted correlation was chosen to be based on the conventional effective temperature ratio (T_g-T_w/T_g-T_a) because its convenient nondimensional form is generally accepted by investigators in the film-cooling field. Since the Parametric Effects on Film Cooling section of this report shows that this ratio appears to be some function of specific weight flow, (s/x), and (T_a/T_g) ratios, the correlation was assumed to take the following form:

$$\frac{T_g - T_w}{T_g - T_a} = K\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^w \left(\frac{s}{x}\right)^y \left(\frac{T_a}{T_g}\right)^z$$

In order to determine the three unknown exponents in the above equation, each parameter was plotted against the effective temperature on log-log scales while holding the other two parameters constant. It should be emphasized that the following three plots (figs. 11, 12, and 13) constitute a sampling only of the complete data of figures 2 to 5 but also represent the general trends.

Figure 11 shows the effective temperature ratio plotted against the distance x for constant specific weight-flow-ratio curves. Mainstream Mach number, slot height, and temperature ratio (T_g/T_a) are held constant. Note the difference in the slopes of the curves within specific regions which indicates the possible need of separate correlating equations to cover the complete range of data. Further observations of data defined four distinct constant-slope regions.

In figure 12 the variable is the specific weight flow ratio plotted against the effective temperature ratio for constant value curves of x. Mainstream Mach number, slot height, and temperature ratio (T_g/T_a) are held constant. Slope changes for three separate regions are indicated in this plot.

The temperature ratio (T_g/T_a) is plotted against the effective temperature ratio in figure 13 for constant x curves. Below an effective temperature ratio of approximately 0.70 a definite temperature-ratio effect is observed. Above this value and for values of x close to the slot discharge position, this effect becomes quite small. These results also indicate separate correlating regions.

It was necessary to attempt to formulate four separate correlations to cover the range of data obtained since a single correlation resulted in excessive scatter due to the large changes of slopes in the different regions indicated in figures 11 to 13. No correlation attempt was made for values of effective temperature ratio below 0.10 because of excessive scatter of data. It was also assumed that the small amount of cooling obtained in this region was of no practical interest.

All the data obtained were plotted in the form of figures 11 to 13. The slopes of the individual curves were measured within the regions indicated, and average values were obtained and applied as exponents to their respective parameters. The determined exponential values were applied with the measured film-cooling data to the assumed form of the correlation in order to evaluate the constant K.

Results of correlation (range and limitations). - The accuracy of the four empirically derived correlations was now determined by calculating an effective temperature ratio using the film-cooling data. Qualifying restrictions had to be made in order to generalize the data. Figure

14 shows plots of the measured against the calculated effective temperature ratio. These plots are an indication of the accuracy of the four correlating equations which were needed to cover the range of data obtained.

The calculated values of effective temperature ratio for figure 14(a) were obtained by using the following equation:

$$\frac{T_g - T_w}{T_g - T_a} = 12.6\left[\frac{(\rho V)_a}{(\rho V)_g}\right]\left(\frac{s}{x}\right)^{0.72}\left(\frac{T_a}{T_g}\right)^{0.5} \tag{1}$$

Restrictions imposed on this correlation limits its usefulness to an effective temperature ratio less than 0.70 and for positions along the test plate greater than 3.5 inches as measured from the slot discharge position. The data on this plot are also limited to a maximum specific weight flow ratio of 2.00 and includes the range of slot heights investigated (1/16 to 1/2 in.). The parallel lines indicate a ± 0.06 band which includes 92.2 percent of all the data obtained which are subject to the above restrictions.

The temperature-ratio parameter $(T_a/T_g)^{0.5}$ appears to correlate this data which is an effect heretofore not reported by investigators in the field. If the theoretical model of reference 2 is assumed to be approximately correct, fluid property differences can account for a parameter value of $(T_a/T_g)^{0.26}$. The balance of this effect may be due to the increase of mixing caused by the increased turbulence level at higher gas temperatures. Previous investigators could not have observed this phenomenon since their data were obtained within a temperature range not subject to measurable fluid-property differences.

The calculated values of effective temperature ratio for figure 14(b) were obtained by using the following equation:

$$\frac{T_g - T_w}{T_g - T_a} = 1.86\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.44}\left(\frac{s}{x}\right)^{0.36} \tag{2}$$

Restrictions imposed on the above equations are similar to those limiting equation (1) except that this correlation holds for positions on the test plate close to the slot exit ($x < 3.5$ in.). The effective temperature ratio is limited to a maximum value of 0.70 and the specific weight flow ratio is limited to a maximum value of 2.00. This plot includes data to cover the range of slot height from 1/16 to 1/2 inch, and 87 percent of the data are included within the ± 0.08 band as indicated by the parallel lines.

The parameter $(T_a/T_g)^{1/2}$ which is included in the previous correlation does not appear here. It is possible that the initial momentum of the cooling stream has sufficient energy near the slot exit to cancel out this effect.

The correlating equations (1) and (2) hold for values of effective temperature ratio less than 0.70. It was also necessary to obtain two equations for effective temperature ratios greater than 0.70. This was due to the slope change of the log-log plots at an (x/s) value of 18.6.

The calculated values of effective temperature ratio for figure 14(c) were obtained by using the following equation:

$$\frac{T_g - T_w}{T_g - T_a} = 1.15\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.18}\left(\frac{s}{x}\right)^{0.11} \tag{3}$$

The above equation holds for values of (x/s) greater than 18.6. In this case where the effective temperature ratio must be greater than 0.70, the specific weight flow ratio had to be limited to a maximum value of 4.0. Under the above restrictions the cooling obtained using the 1/16-inch slot was quite ineffective, therefore, this correlation holds for values of slot heights between 1/8 and 1/2 inch. Within the ±0.08 band indicated by the parallel lines, 89.3 percent of the data is included.

For figure 14(d) the calculated values of effective temperature ratio were obtained using the following equation:

$$\frac{T_g - T_w}{T_g - T_a} = 0.83\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.18} \tag{4}$$

Restrictions on the above equation are similar to those limiting equation (3) except that this correlation holds for (x/s) values less than 18.6. Effective temperature ratios must be greater than 0.70 and the maximum value of specific weight flow ratio is equal to 4.00. The values of slot heights must also be between 1/8 and 1/2 inch. In this case 93.7 percent of the data are included within the ±0.08 band as indicated by the parallel lines. Note that within the above restrictions the effective temperature ratio is merely a function of specific weight flow ratio.

It should be noted that equations (3) and (4) do not include the $(T_a/T_g)^{0.5}$ term. It appears that for effective temperature ratios greater than 0.70 the increased initial momentum of the higher weight flow cooling gas helps maintain the identity of the cooling film and thus cancel out the temperature-ratio effect.

The four plots of figure 14 which are an indication of the accuracy of the correlating equations also show the extent of the data scatter. Although the parallel lines, which include most of the data, indicate that the scatter can vary from approximately 10 percent at high values of effective temperature ratio to 70 percent at low values, it can be seen that the variation in wall temperature is a constant over the range of each correlation.

For example, in figure 14(a) if it were assumed that $T_g = 2000^\circ$ R and $T_a = 500^\circ$ R, then a simple calculation would show that the scatter in the data results in a 180° maximum difference in wall temperature which is constant over the range of correlation.

The following table lists the four correlating equations obtained in the present investigation with their respective limitations.

Correlating equations	$\frac{T_g-T_w}{T_g-T_a}$ (range)	Applicable distance (range), in.	Maximum, $\frac{(\rho V)_a}{(\rho V)_g}$	Slot height (range), in.
(1) $\frac{T_g-T_w}{T_g-T_a} = 12.6\left[\frac{(\rho V)_a}{(\rho V)_g}\right]\left(\frac{s}{x}\right)^{0.72}\left(\frac{T_a}{T_g}\right)^{0.5}$	0.1 to 0.7	$x > 3.5$	2.0	$\frac{1}{16}$ to $\frac{1}{2}$
(2) $\frac{T_g-T_w}{T_g-T_a} = 1.86\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.44}\left(\frac{s}{x}\right)^{0.36}$	0.1 to 0.7	$x < 3.5$	2.0	$\frac{1}{16}$ to $\frac{1}{2}$
(3) $\frac{T_g-T_w}{T_g-T_a} = 1.15\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.18}\left(\frac{s}{x}\right)^{0.11}$	0.7 to 1.0	$\frac{x}{s} > 18.6$	4.0	$\frac{1}{8}$ to $\frac{1}{2}$
(4) $\frac{T_g-T_w}{T_g-T_a} = 0.83\left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.18}$	0.7 to 1.0	$\frac{x}{s} < 18.6$	4.0	$\frac{1}{8}$ to $\frac{1}{2}$

It is again emphasized that the above equations were obtained using air for both the heating and coolant flows, and therefore cannot be applied to gases having fluid properties other than air. It should also be noted that no theoretical confirmation was obtained for the right to extrapolate these equations for use at temperatures higher than those employed in the present investigation.

SUMMARY OF RESULTS

An experimental investigation was made to determine the characteristics of axially discharging, single-slot film cooling of an adiabatic wall exposed to a hot gas stream. The test plate was the top wall of an 8- by 8-inch rectangular duct 36 inches in length. The temperature of the mainstream gas ranged from 520° to 2000° R and the mainstream Mach number was varied from 0.15 to 0.70. The temperature of the cooling air ranged from 540° to 870° R and the cooling-air Mach number was varied from 0 to 1.0. In most cases the slot was choked for the maximum weight flows. Basic nondimensional data plots for the four slot heights investigated (1/2, 1/4, 1/8, and 1/16 in.) are herein presented.

A data correlation covering the range of effective temperature ratios from 0.1 to 1.0 was obtained using four variations of a basic correlating equation. The four equations and their limitations were included.

Within the range of data covered by the correlating equations it was found that the independent variation of mainstream Mach number had very little effect on film-cooling performance. It was also determined that within certain restrictions the effective temperature ratio generalizes as a function of the (x/s) parameter.

An evaluation of the data showed a definite temperature-ratio effect for values of effective temperature ratio less than 0.70 and values of x along the test plate greater than 3.5 inches. Within this particular range of conditions, it was found that the data could be correlated by employing a parameter of the form $(T_a/T_g)^{0.5}$.

A cursory examination was made to determine the effect on the wall temperature of varying the cooling-air temperature independently. Within the data examined it was found that the difference in wall temperatures was limited to positions along the test plate relatively near the injection point.

Film-heating data were obtained to extend the range of temperature ratios by discharging hot gas through the slot thereby heating the test plate which was cooled by low-temperature mainstream gas. The results correlate with the general data obtained in this investigation and agree fairly well with published data.

Lewis Research Center
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TABLE I. - DATA RUNS

Figure	Gas-flow-passage dimensions				Main-stream temperature, T_g, °R	Slot gas temperature, T_a, °R	T_g/T_a	Main-stream Mach number, M_g	Main-stream weight flow, W, lb/sec
	Slot height, s, in.		Slot area, A_a, sq in.	Main-stream area, A_g, sq in.					
	Nominal	Actual							
2(a)	1/2	0.50	3.60	60.06	1495	550	2.718	0.78	20.4
(b)					1505	540	2.787	.54	11.5
(c)					1510	540	2.796	.23	6.1
(d)					990	540	1.833	.75	22.5
(e)					1000	538	1.859	.53	13.9
(f)					1020	545	1.872	.22	7.0
(g)					1480	880	1.682	.70	20.5
(h)					1495	875	1.709	.50	11.5
(i)					1510	860	1.756	.20	6.3
(j)					810	530	1.528	.50	15.8
(k)					520	955	.545	.50	18.6
3(a)	1/4	0.26	1.733	61.91	1963	630	3.111	.53	12.2
(b)					1470	575	2.557	.68	17.0
(c)					1480	560	2.643	.45	13.0
(d)					1493	560	2.666	.22	6.0
(e)					1055	545	1.936	.15	5.1
(f)					980	540	1.815	.73	24.7
(g)					990	548	1.807	.52	14.1
(h)					990	540	1.833	.23	9.3
4(a)	1/8	0.135	0.882	62.84	1485	550	2.700	.70	20.2
(b)					1490	545	2.734	.51	11.6
(c)					1500	545	2.752	.22	6.0
(d)					995	540	1.843	.70	22.6
(e)					990	538	1.840	.50	14.0
(f)					1010	536	1.884	.23	7.2
(g)					1500	875	1.714	.70	18.5
(h)					1490	875	1.703	.50	12.1
(i)					1505	880	1.710	.20	5.9
5(a)	1/16	0.063	0.442	63.30	1495	557	2.684	.70	18.6
(b)					1490	550	2.709	.49	11.4
(c)					1490	548	2.719	.22	6.1
(d)					1000	544	1.838	.70	22.7
(e)					1005	540	1.861	.50	13.9
(f)					1010	543	1.860	.20	6.7

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TABLE II. - INSTRUMENTATION

(a) Rig

Station or location on figure 1(b)	Total pressure, P	Static pressure, p	Thermocouples
Mainstream air, station (1)	Four-radial, six-probe equal-area rakes 90° apart Two-radial, four-probe boundary-layer rakes	Four wall taps	Twelve
Cooling air, station (3)	Three orifice runs, each containing one probe	Three orifice runs each containing two taps	Three orifice runs each containing one probe
Slot discharge, station (2)		Ten wall taps	Two
Slot box, section (a)		One wall tap	Three

(b) Test plate

Measuring position, section (b)	Distance from slot, in.	Thermocouples	Static pressures, p
x_1	1.58	3	1
x_2	2.51	3	4
x_3	4.51	3	1
x_4	6.51	3	4
x_5	8.51	3	1
x_6	10.51	1	1
x_7	12.51	3	4
x_8	15.51	1	1
x_9	18.01	1	1
x_{10}	21.01	1	1
x_{11}	24.01	3	4
x_{12}	33.91	3	4

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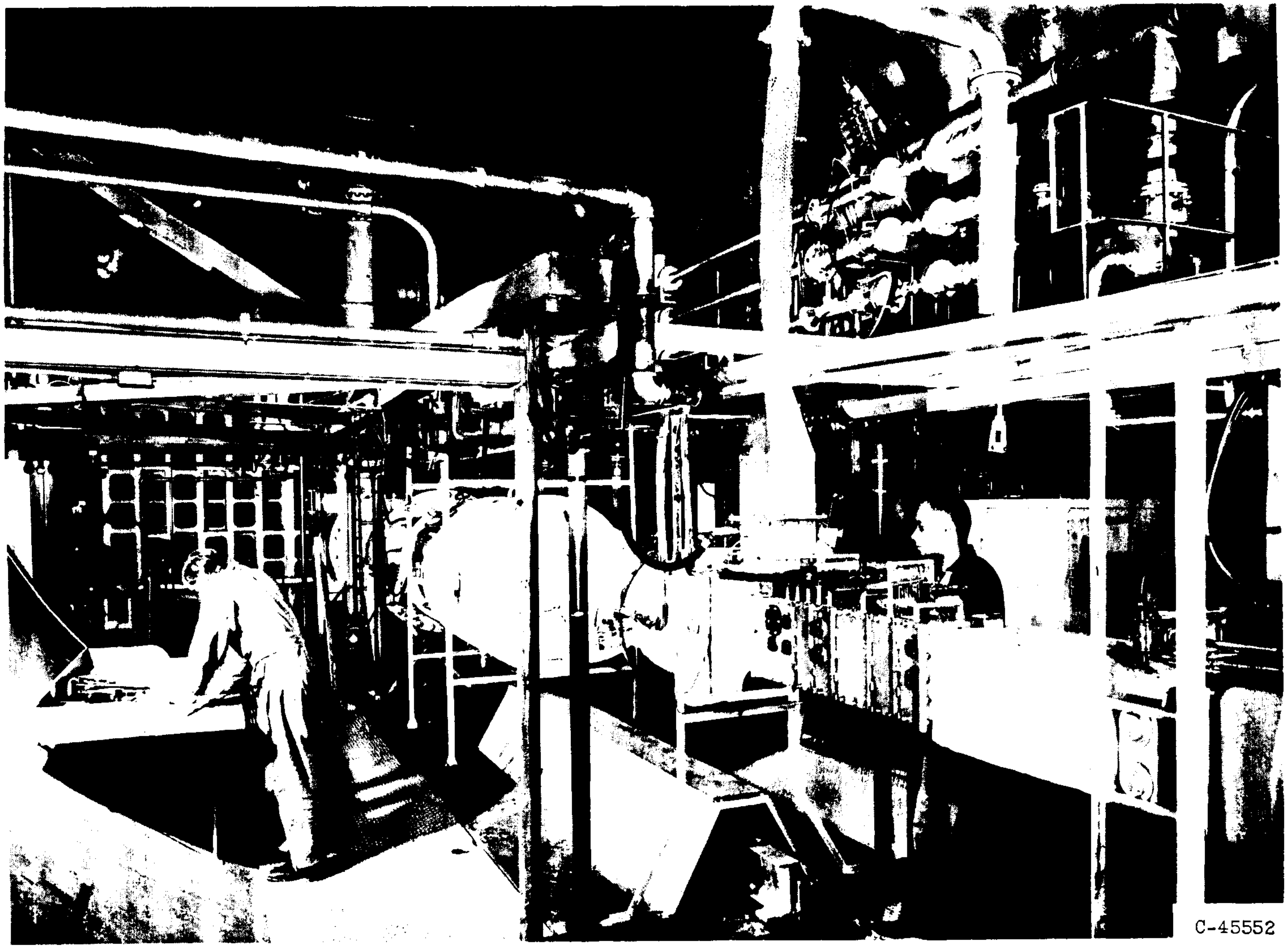
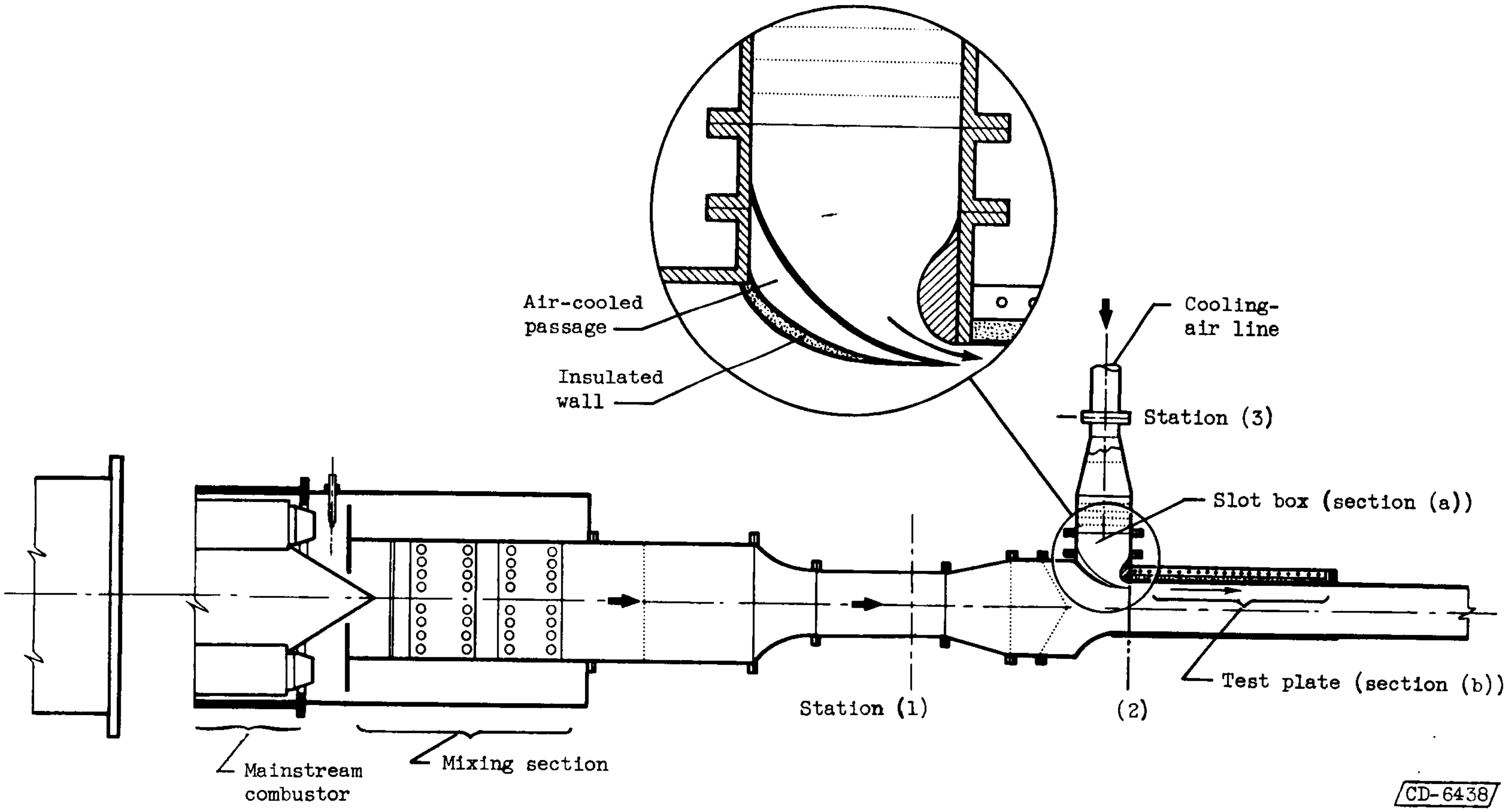


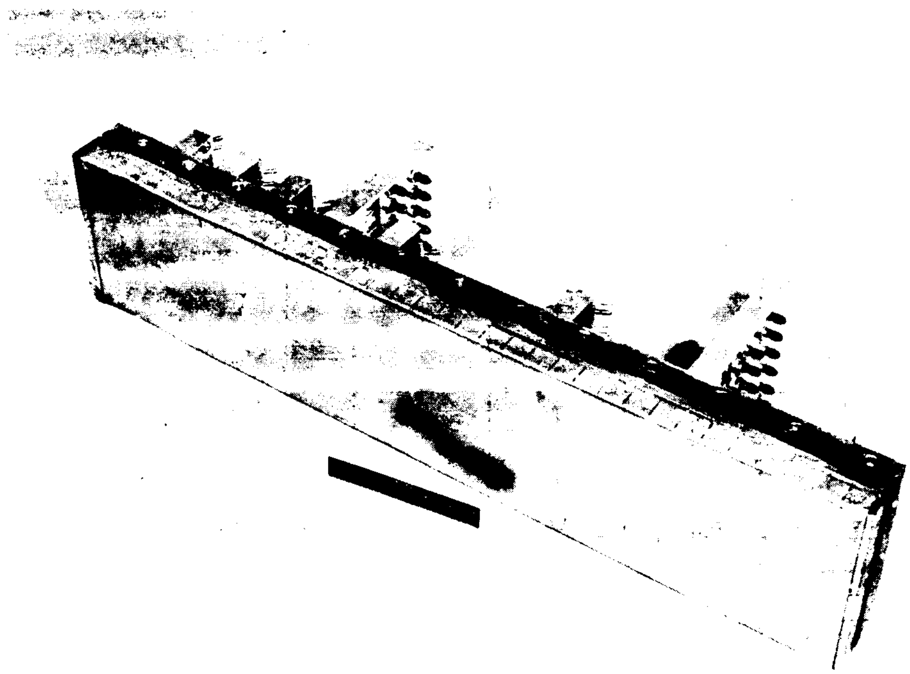
(a) Rig before insulation of the test section.

Figure 1. - Film-cooling test facility.

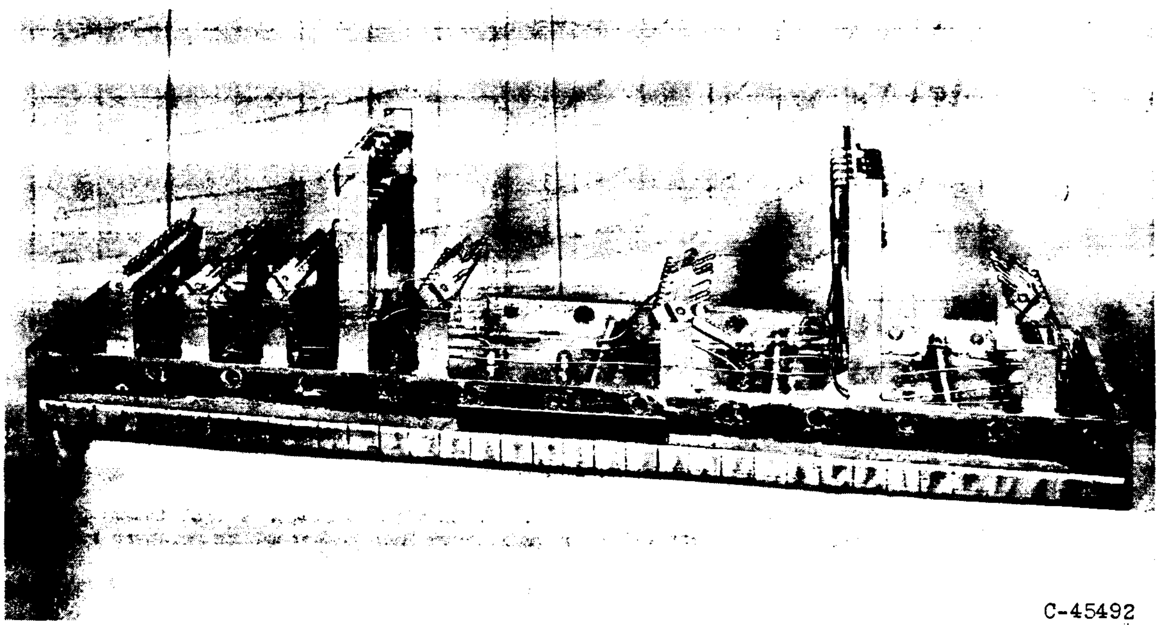


(b) Schematic diagram of complete test assembly.

Figure 1. - Continued. Film-cooling test facility.



C-45493



C-45492

(c) Two views of test plate.

Figure 1. - Concluded. Film-cooling test facility.

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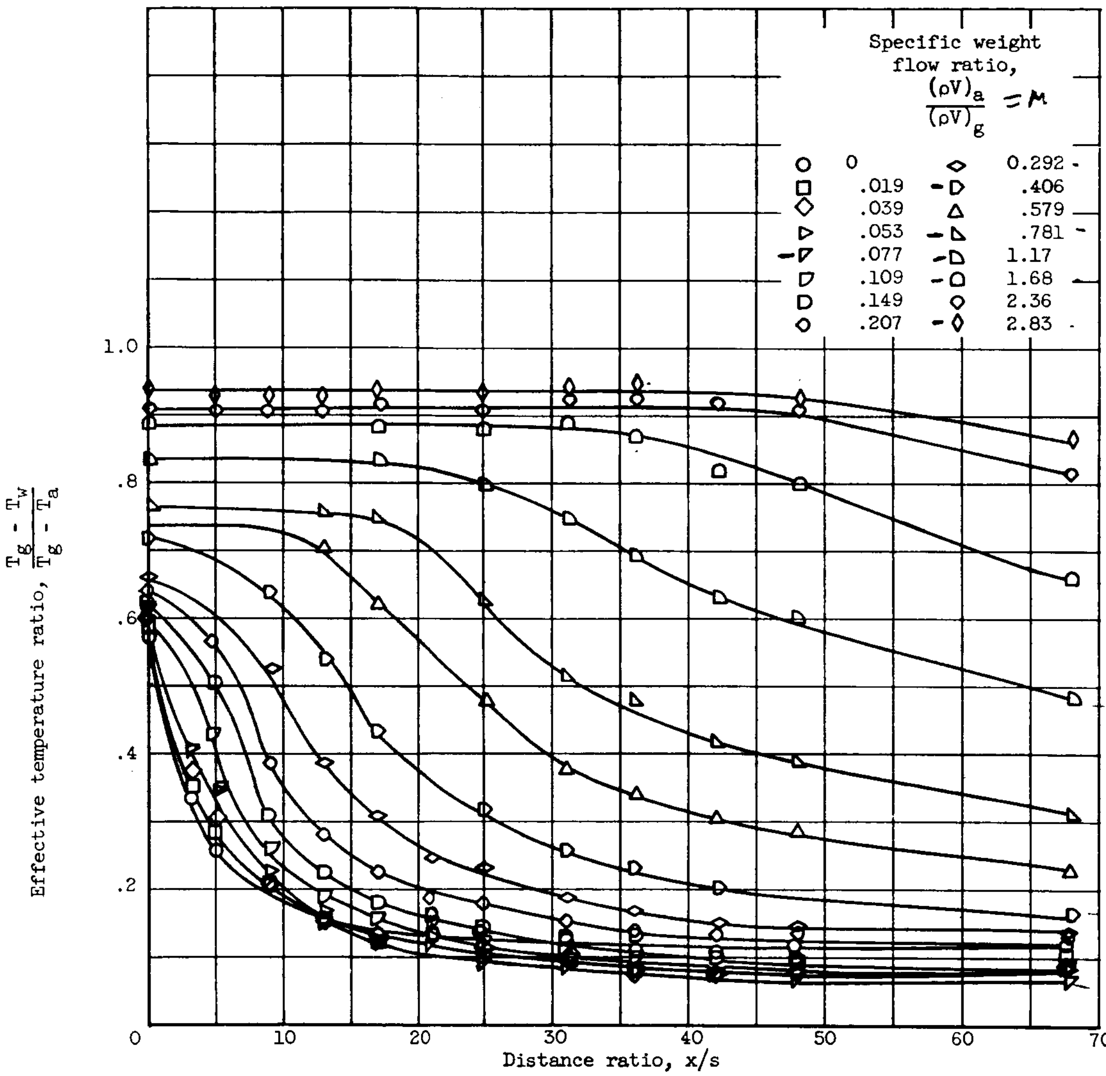
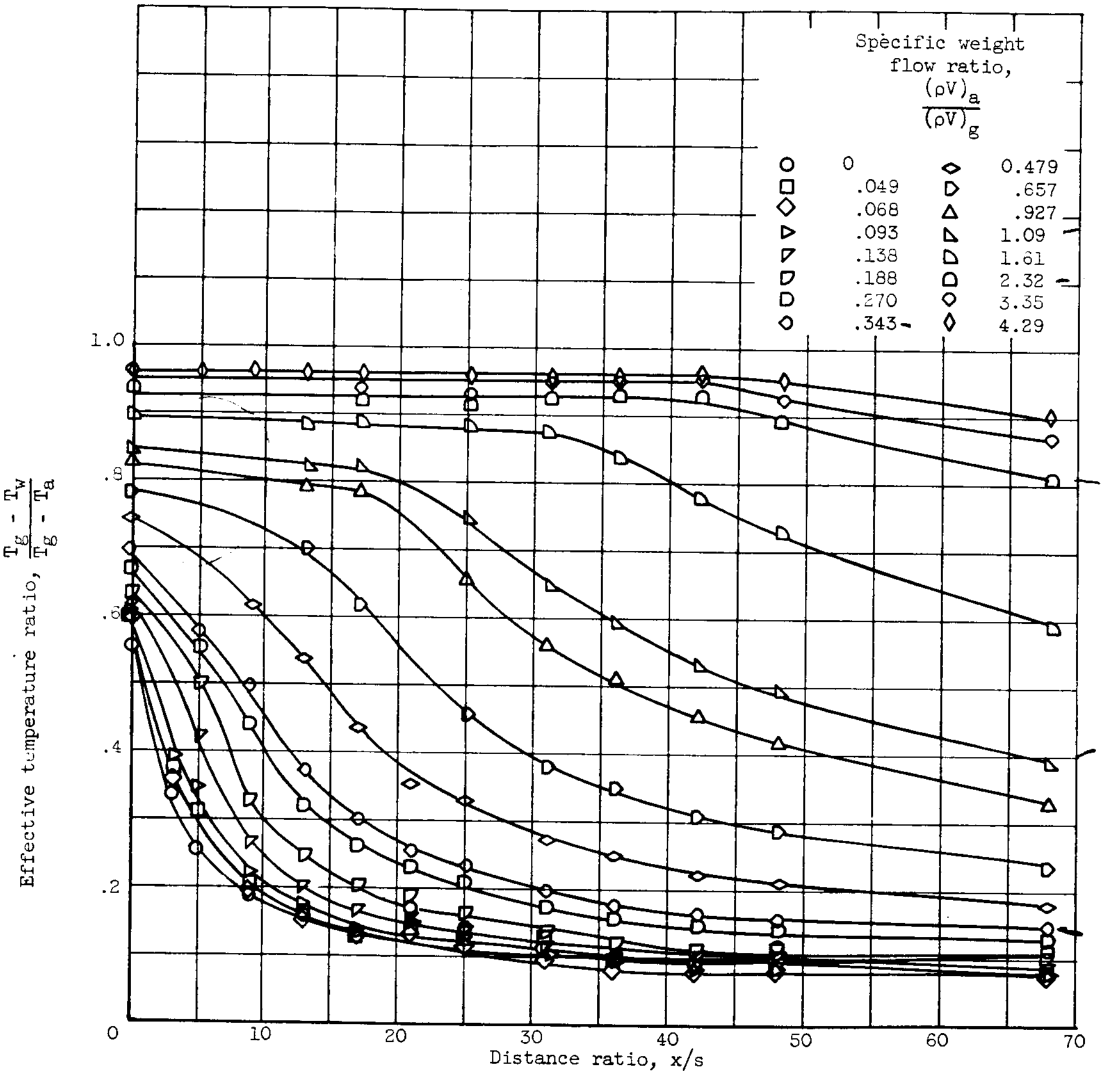
CV-3 back



(a) Mainstream gas temperature, 1495° R; slot gas temperature, 550° R; temperature ratio, 2.718; mainstream Mach number, 0.78.

Figure 2. - Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

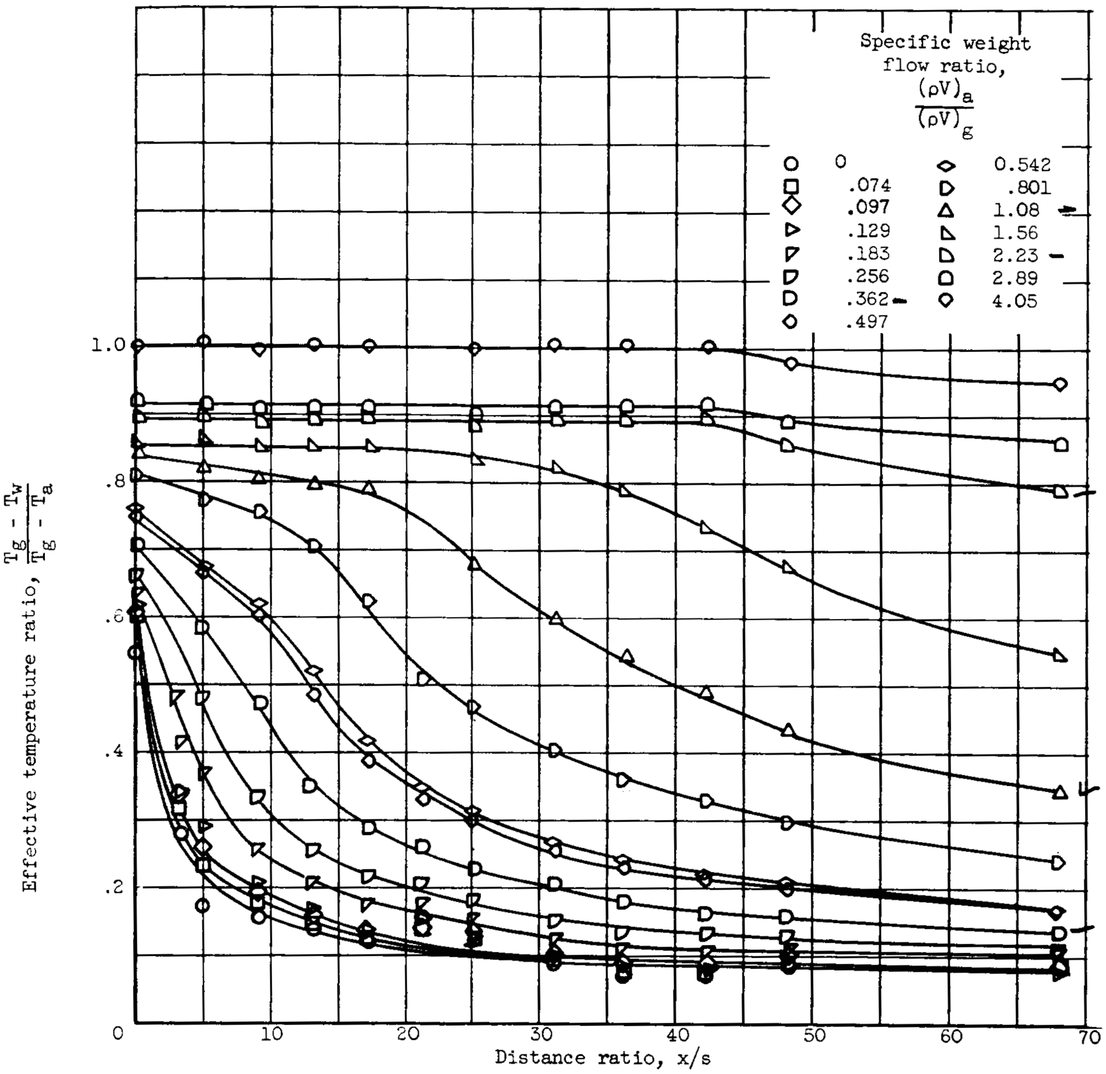
E-212



(b) Mainstream gas temperature, 1505° R; slot gas temperature, 540° R; temperature ratio, 2.787; mainstream Mach number, 0.54.

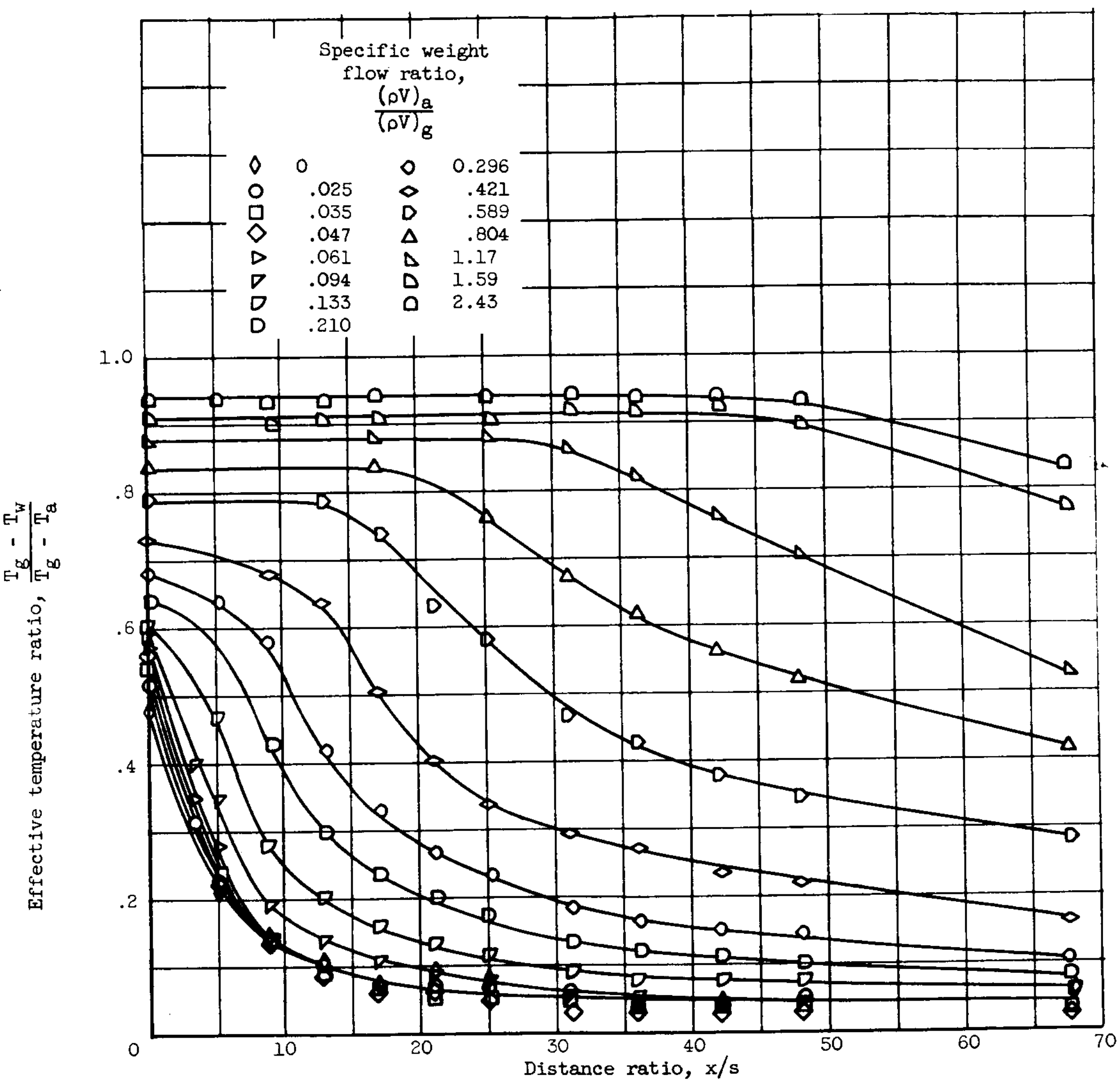
Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

E-212



(c) Mainstream gas temperature, 1510° R, slot gas temperature, 540° R; temperature ratio, 2.796; mainstream Mach number, 0.23.

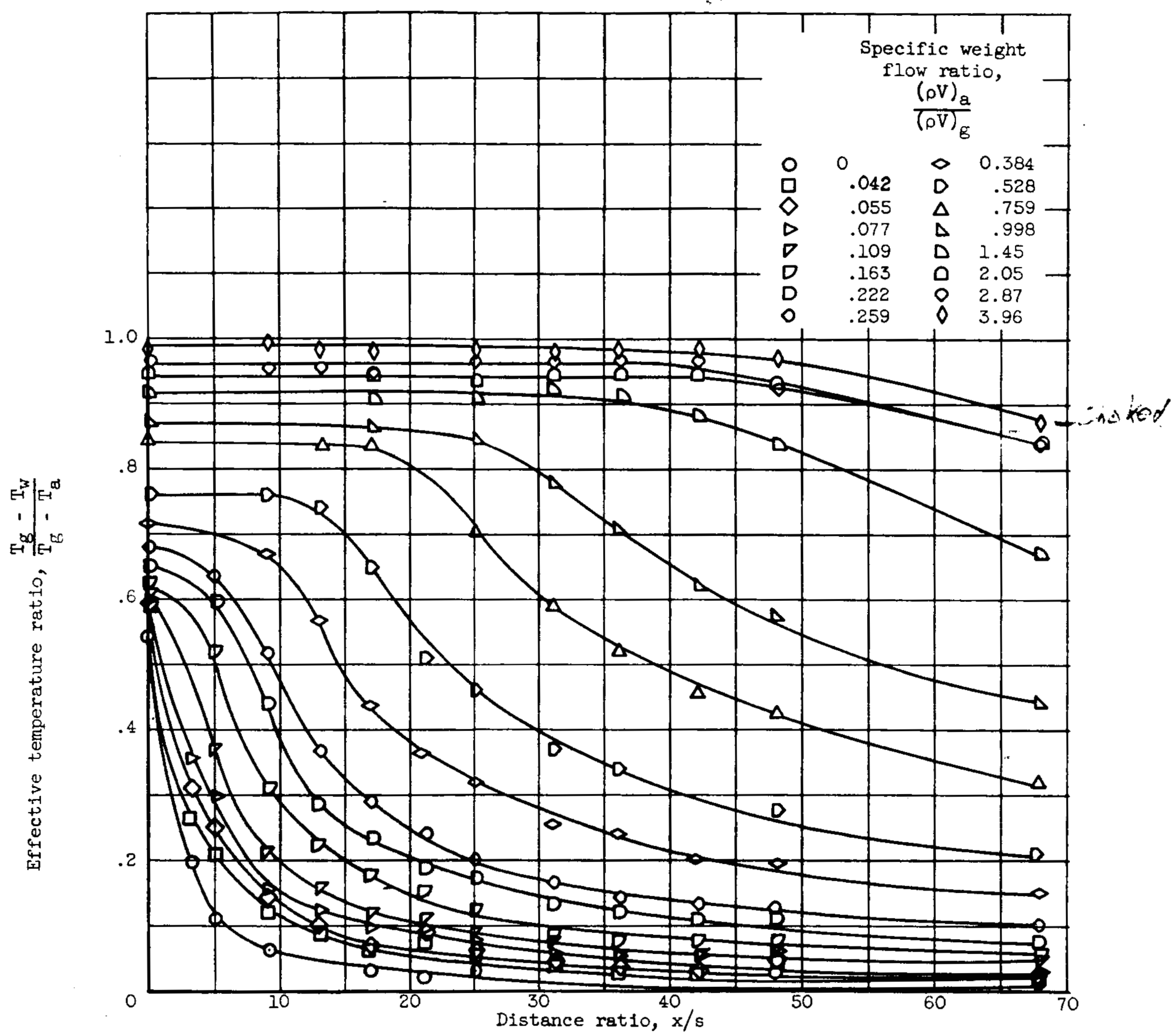
Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.



(d) Mainstream gas temperature, 990° R; slot gas temperature, 540° R; temperature ratio, 1.833; mainstream Mach number, 0.75.

Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

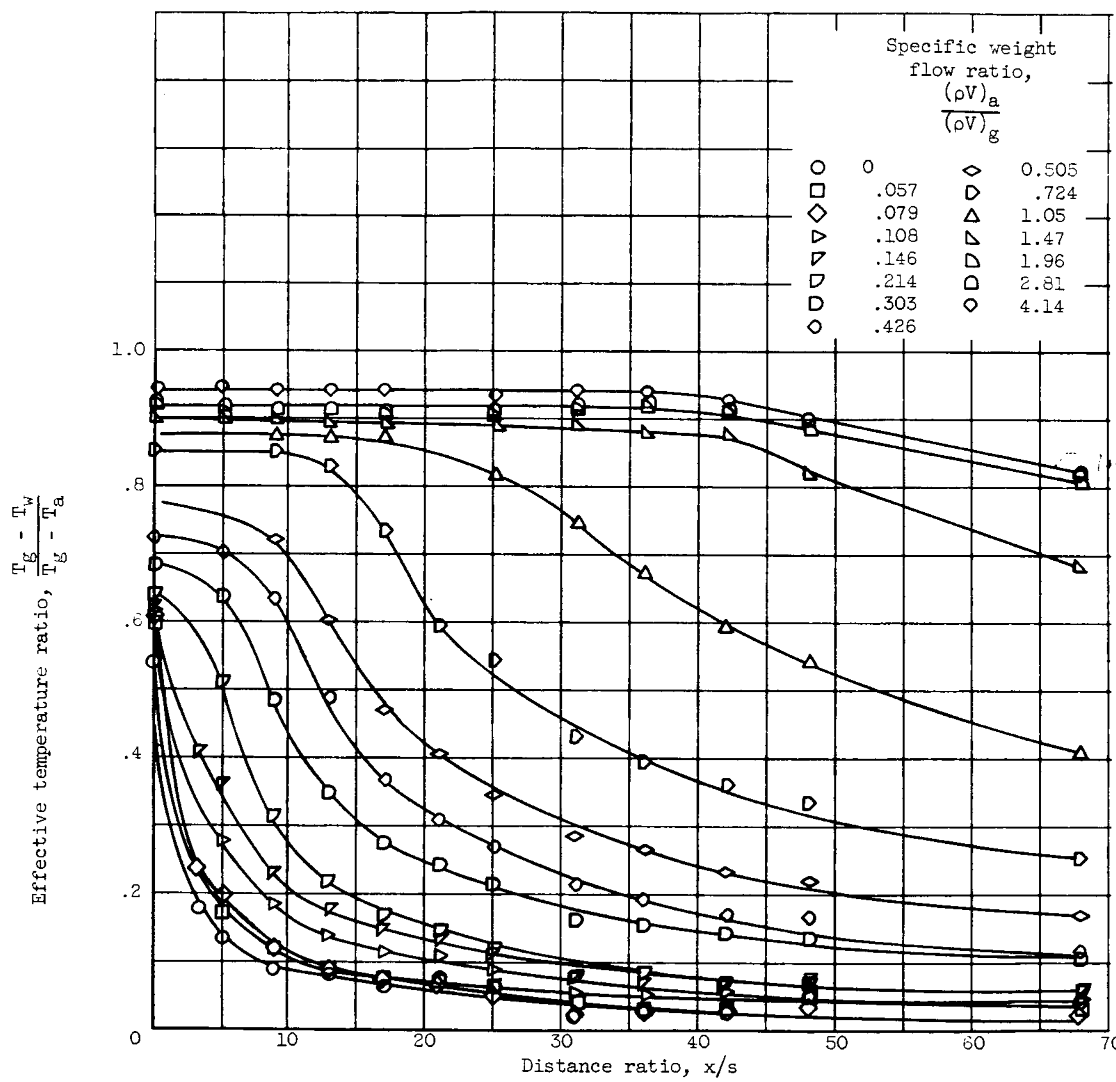
E-272



(e) Mainstream gas temperature, 1000° R; slot gas temperature, 538° R; temperature ratio, 1.859; mainstream Mach number, 0.53.

Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

E-212

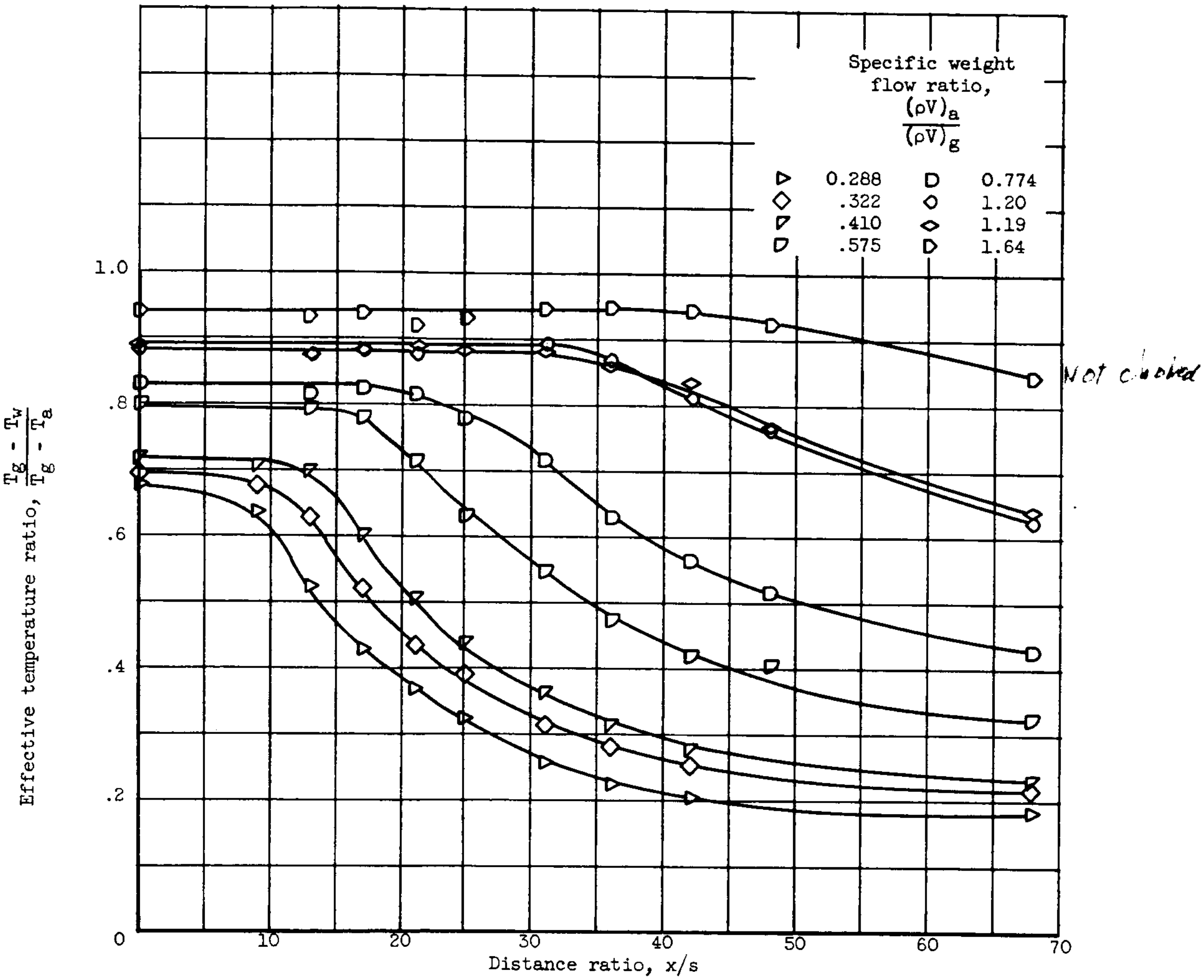


(f) Mainstream gas temperature, 1020° R; slot gas temperature, 545° R; temperature ratio, 1.872; mainstream Mach number, 0.22.

Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

E-212

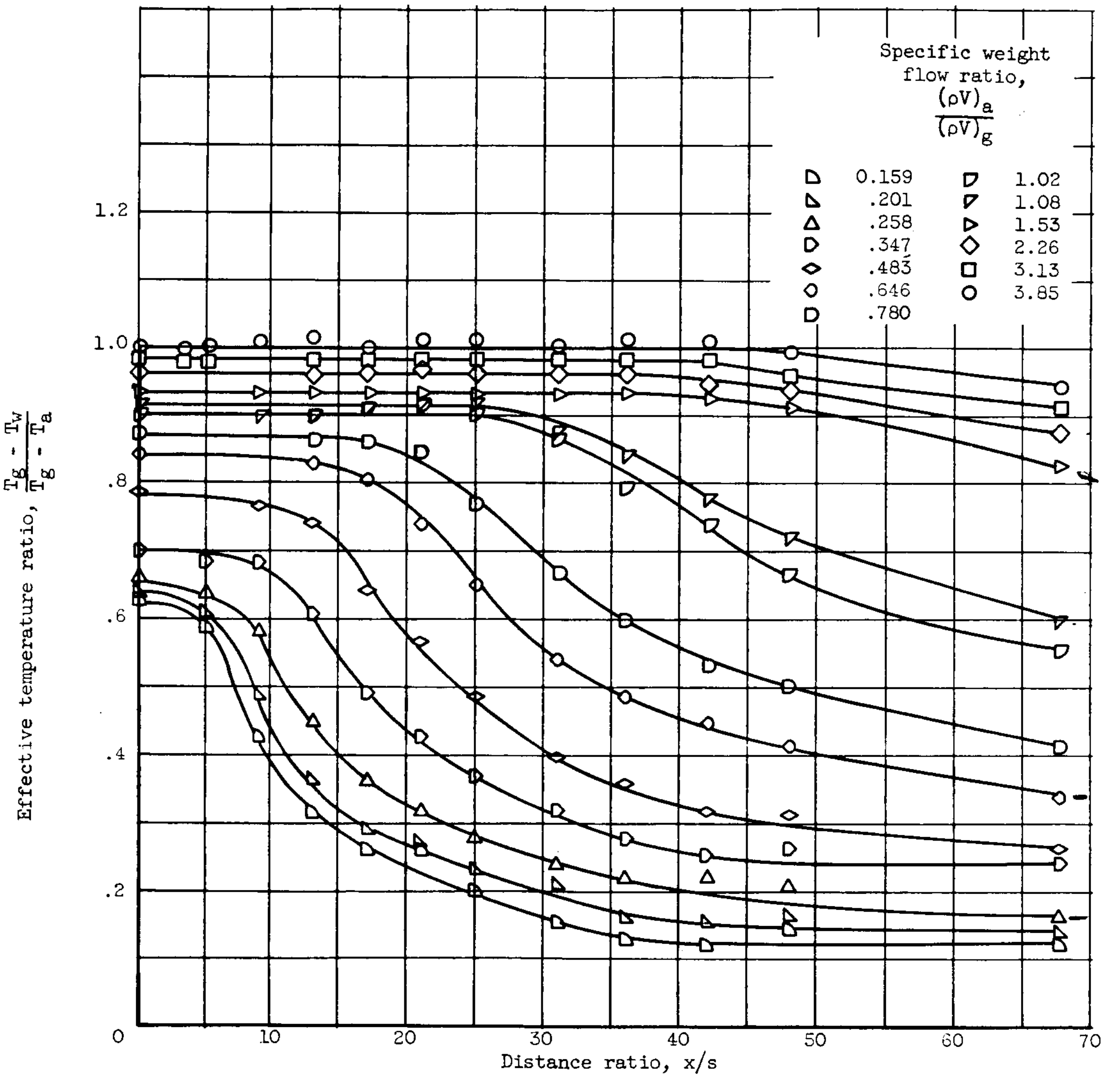
CV-4



(g) Mainstream gas temperature, 1480° R; slot gas temperature, 880° R; temperature ratio, 1.682; mainstream Mach number, 0.70.

Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

E-212

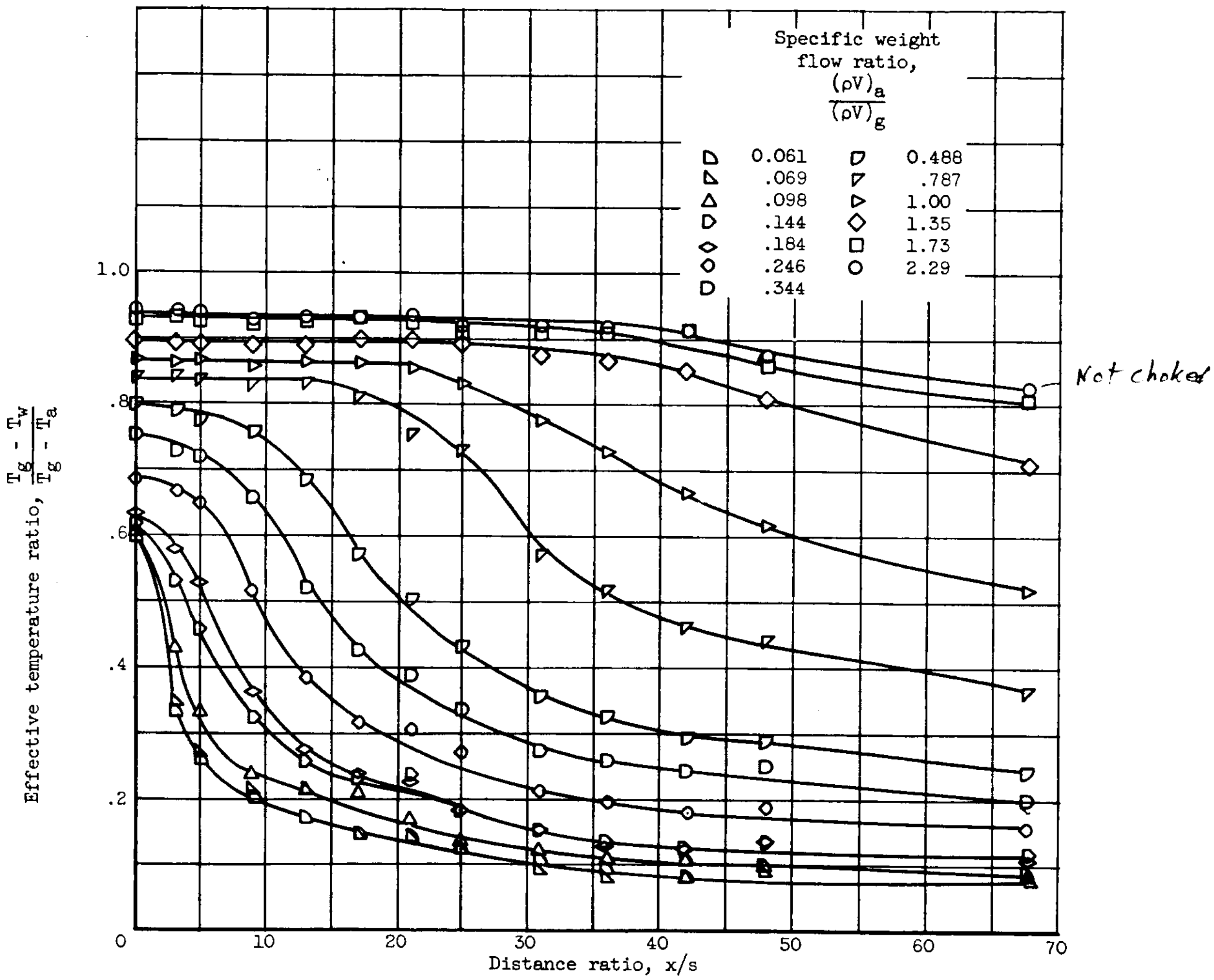


(h) Mainstream gas temperature, 1495° R; slot gas temperature, 875° R; temperature ratio, 1.709; mainstream Mach number, 0.50.

Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

E-212

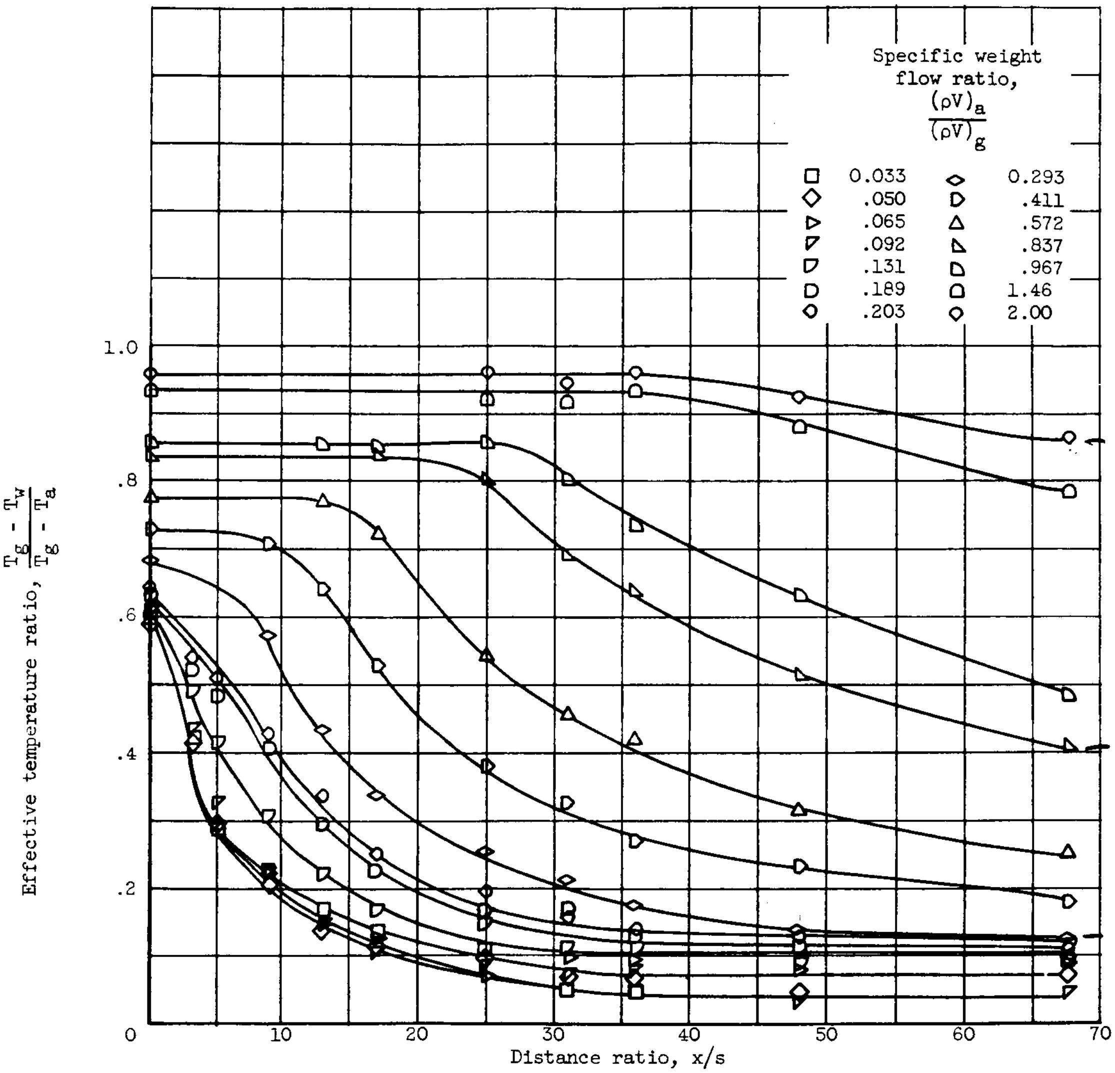
CV-4 back



(i) Mainstream gas temperature, 1510° R; slot gas temperature, 860° R; temperature ratio, 1.756; mainstream Mach number, 0.20.

Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

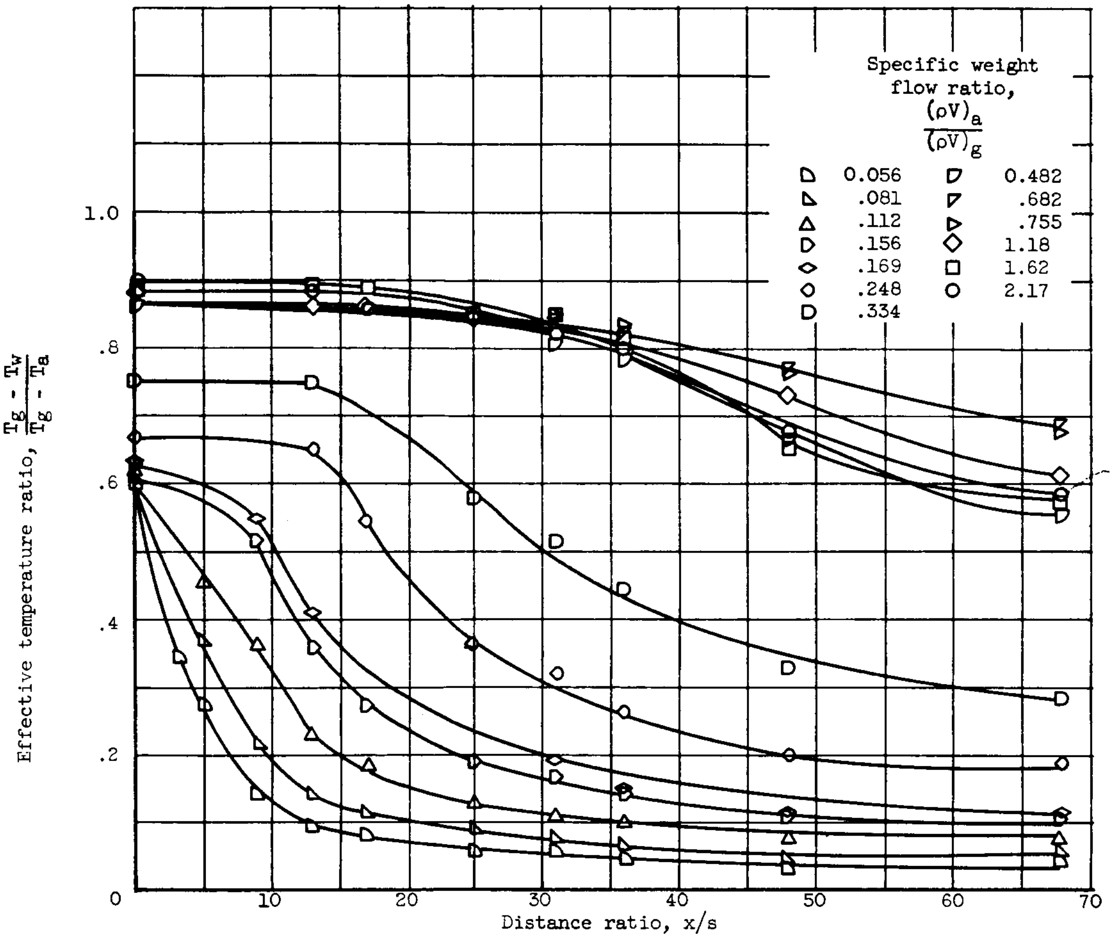
E-212



(j) Mainstream gas temperature, 810° R; slot gas temperature, 530° R; temperature ratio, 1.589; mainstream Mach number, 0.50.

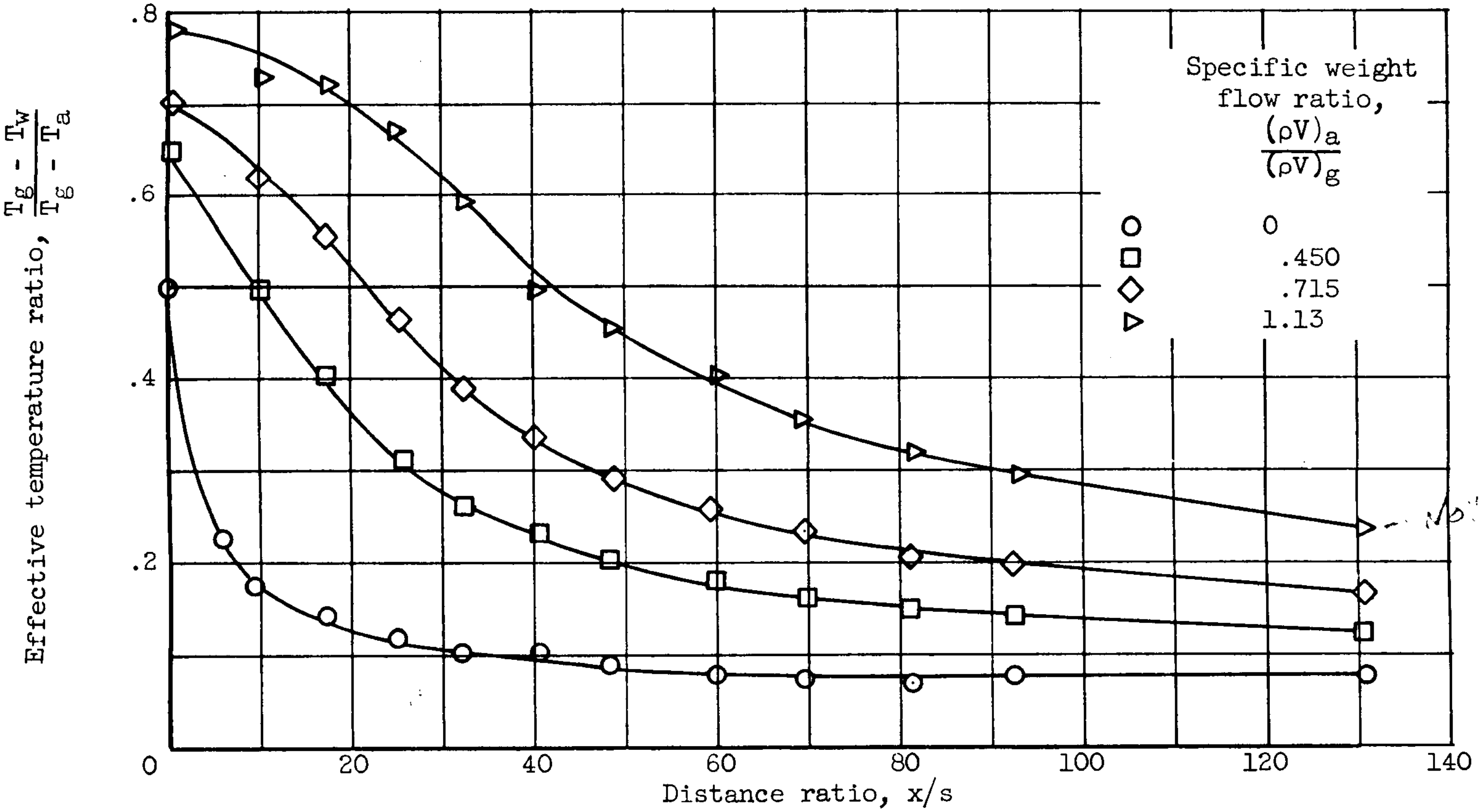
Figure 2. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.

E-212



(k) Mainstream gas temperature, 520° R; slot gas temperature, 955° R; temperature ratio, 0.545; mainstream Mach number, 0.50.

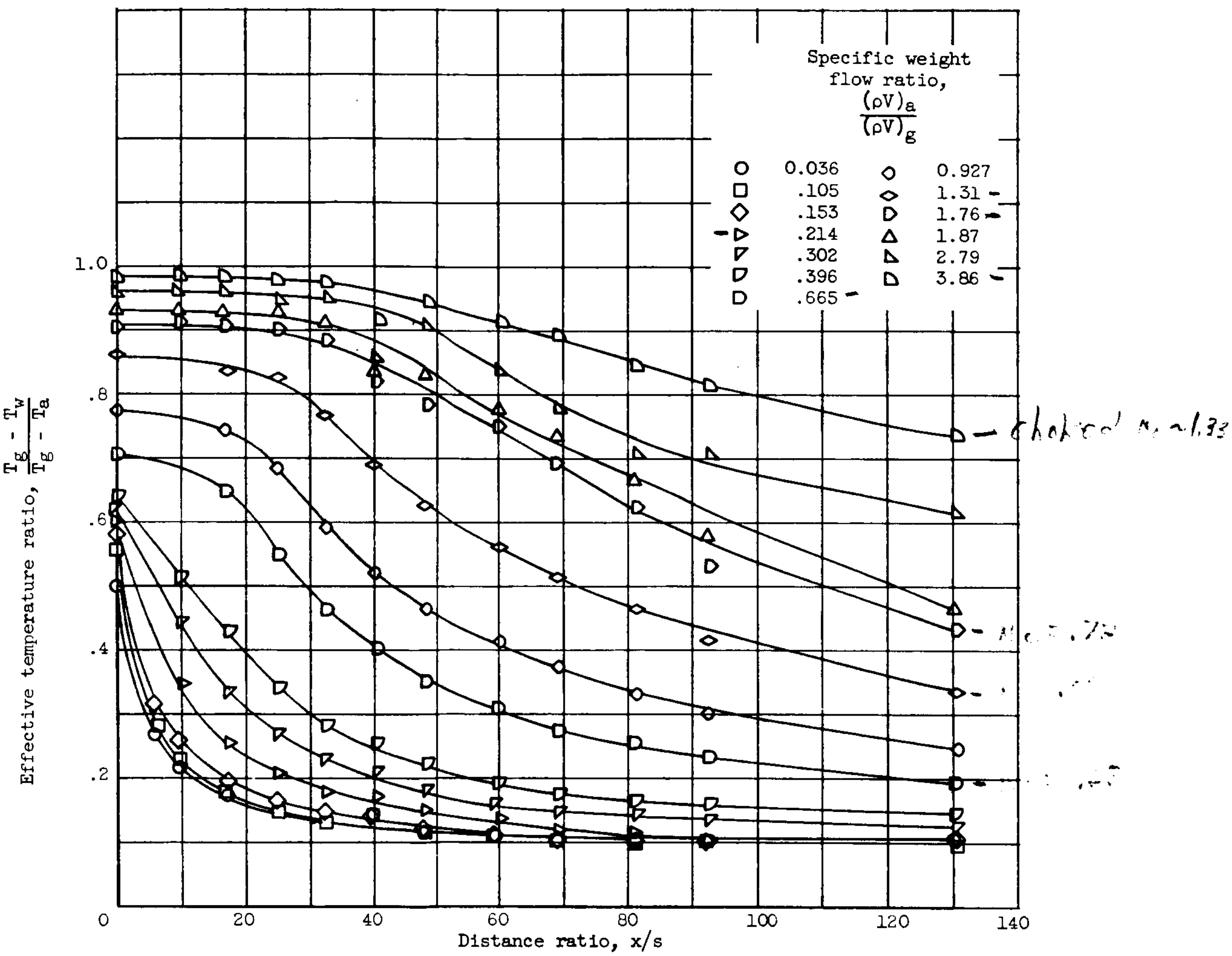
Figure 2. - Concluded. Specific-weight-flow-ratio effect on film cooling at a slot height of one-half inch and constant values of mainstream Mach number and temperature ratio.



(a) Mainstream gas temperature, 1963° R; slot gas temperature, 630° R; temperature ratio, 3.111; mainstream Mach number, 0.53.

Figure 3. - Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.

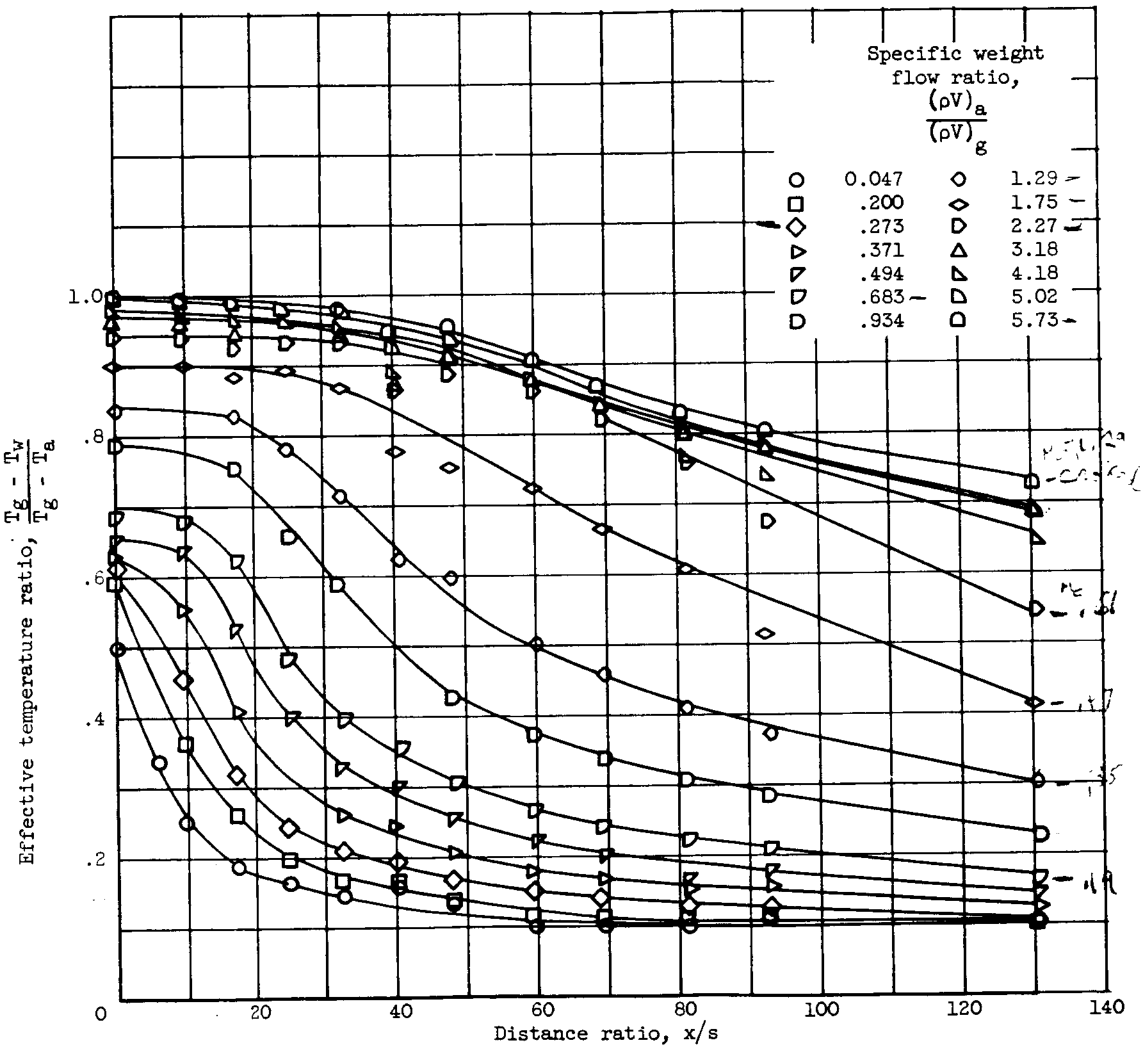
E-212



(b) Mainstream gas temperature, 1470° R; slot gas temperature, 575° R; temperature ratio, 2.56; mainstream Mach number, 0.68.

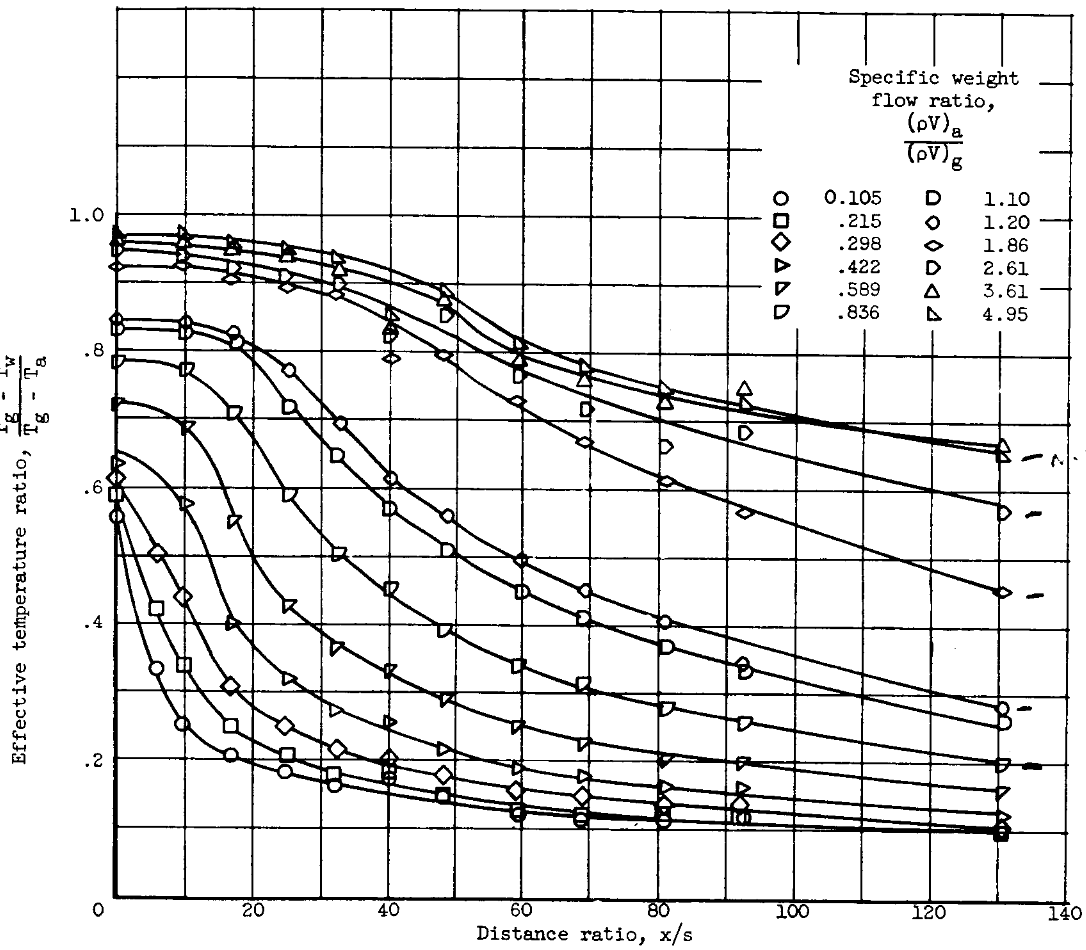
Figure 3. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.

E-212



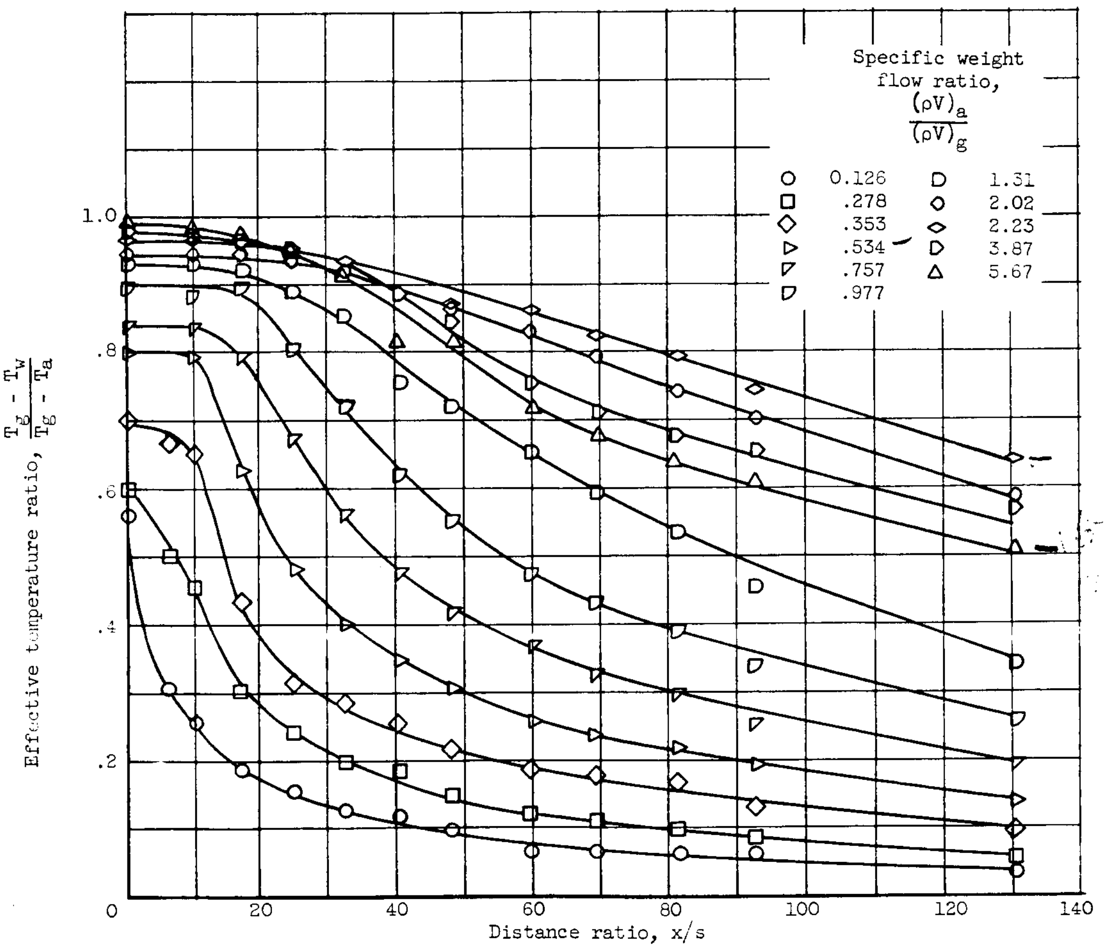
(c) Mainstream gas temperature, 1480° R; slot gas temperature, 560° R; temperature ratio, 2.64; mainstream Mach number, 0.45.

Figure 3. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.



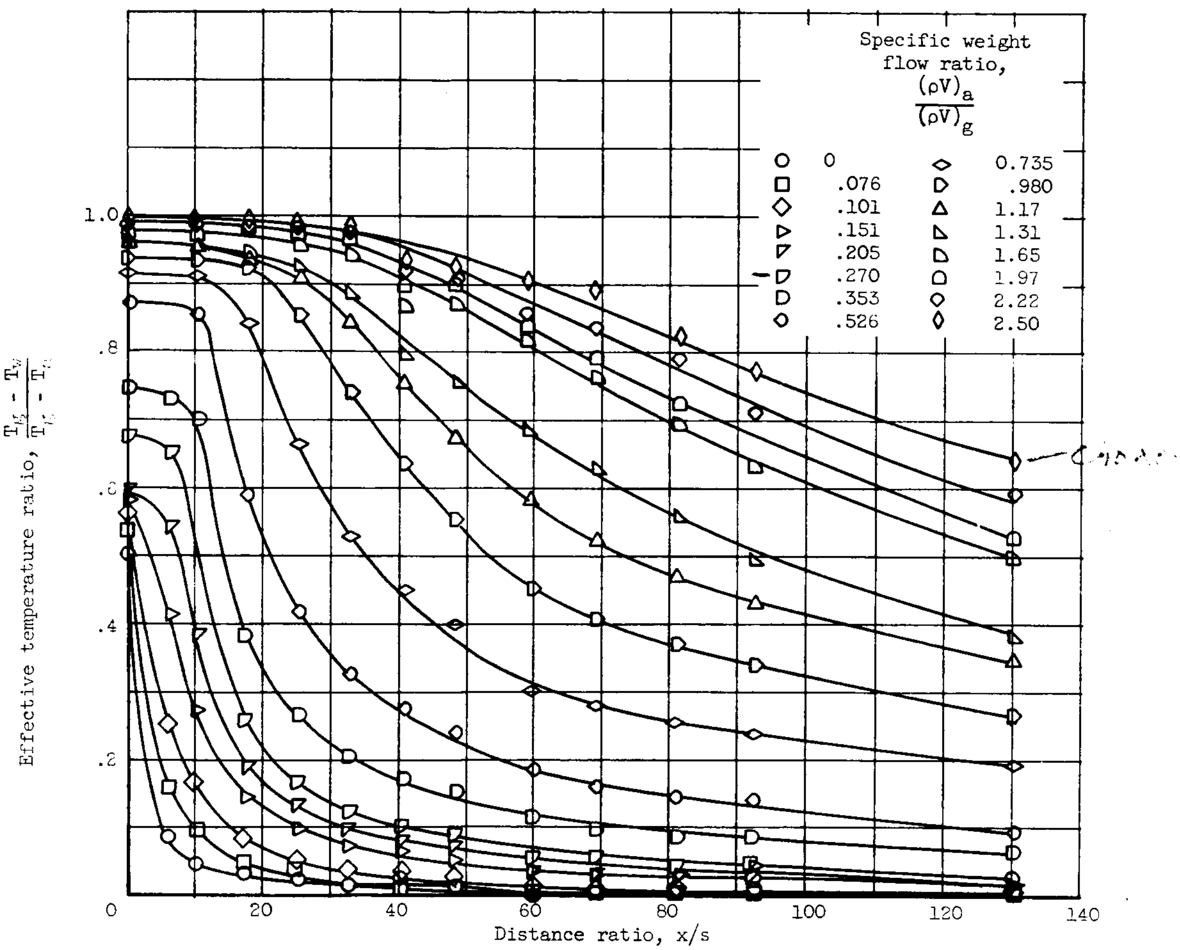
(d) Mainstream gas temperature, 1493° R; slot gas temperature, 560° R; temperature ratio, 2.67; mainstream Mach number, 0.22.

Figure 3. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.



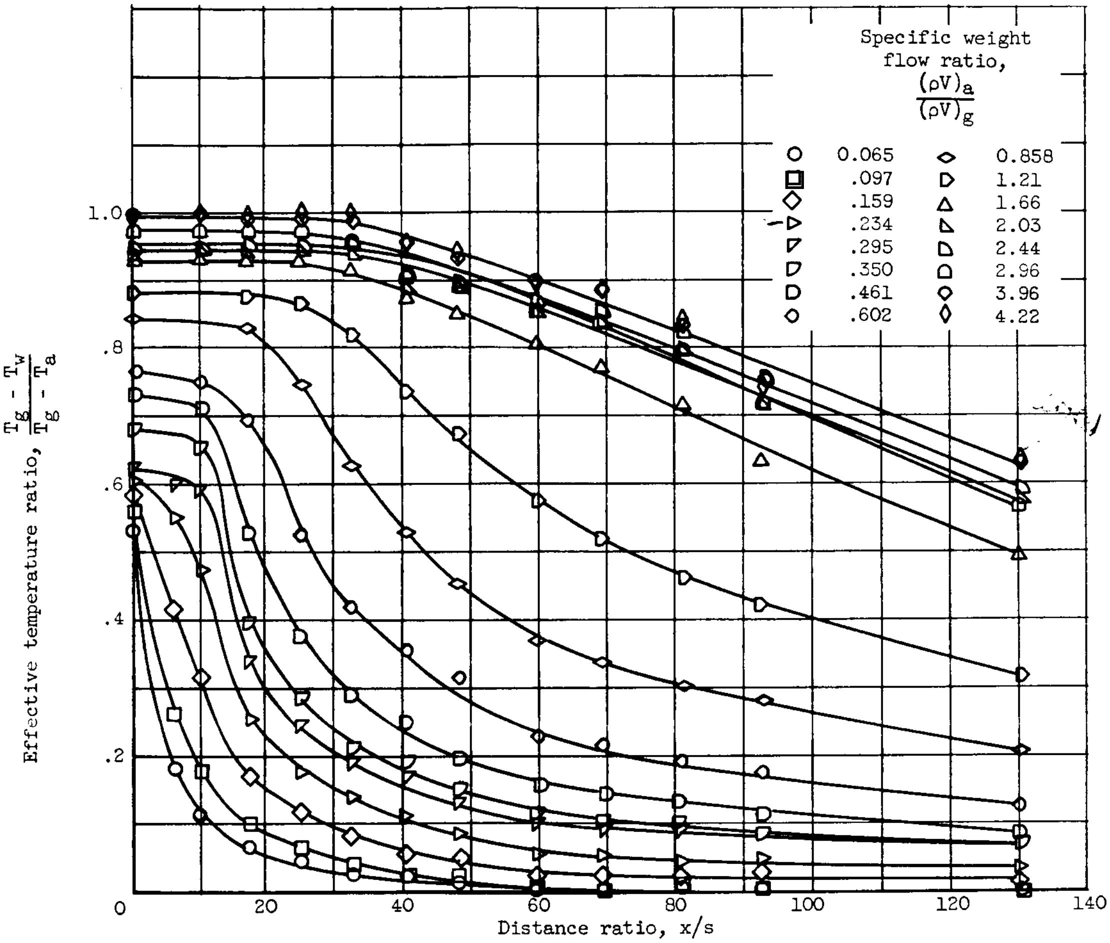
(e) Mainstream gas temperature, 1055° R; slot gas temperature, 545° R; temperature ratio, 1.96; mainstream Mach number, 0.15.

Figure 3. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.



(f) Mainstream gas temperature, 980° R; slot gas temperature, 540° R; temperature ratio, 1.815; mainstream Mach number, 0.73.

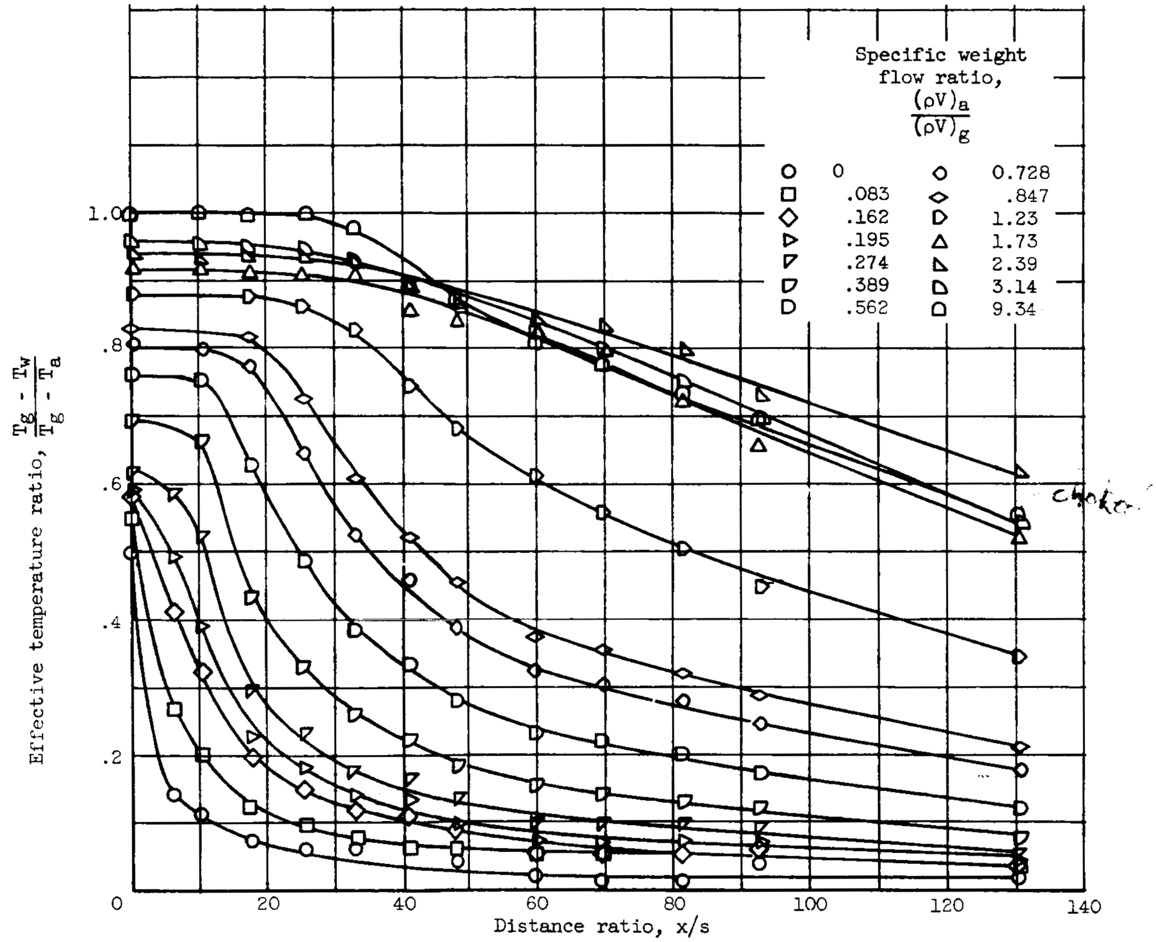
Figure 3. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.



(g) Mainstream gas temperature, 990° R; slot gas temperature, 548° R; temperature ratio, 1.807; mainstream Mach number, 0.52.

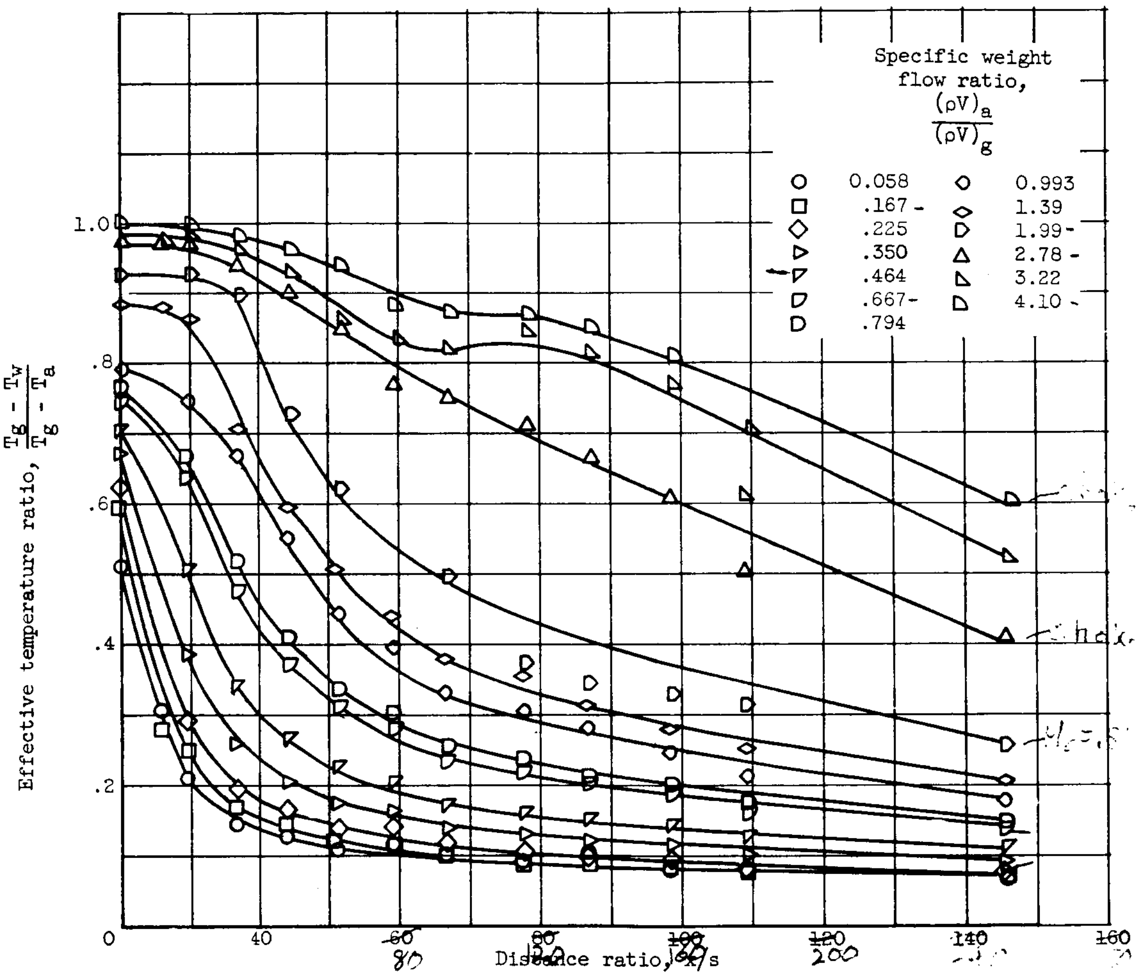
Figure 3. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.

E-212



(h) Mainstream gas temperature, 990° R; slot gas temperature, 540° R; temperature ratio, 1.833; mainstream Mach number, 0.23.

Figure 3. - Concluded. Specific-weight-flow-ratio effect on film cooling at a slot height of one-fourth inch and constant values of mainstream Mach number and temperature ratio.

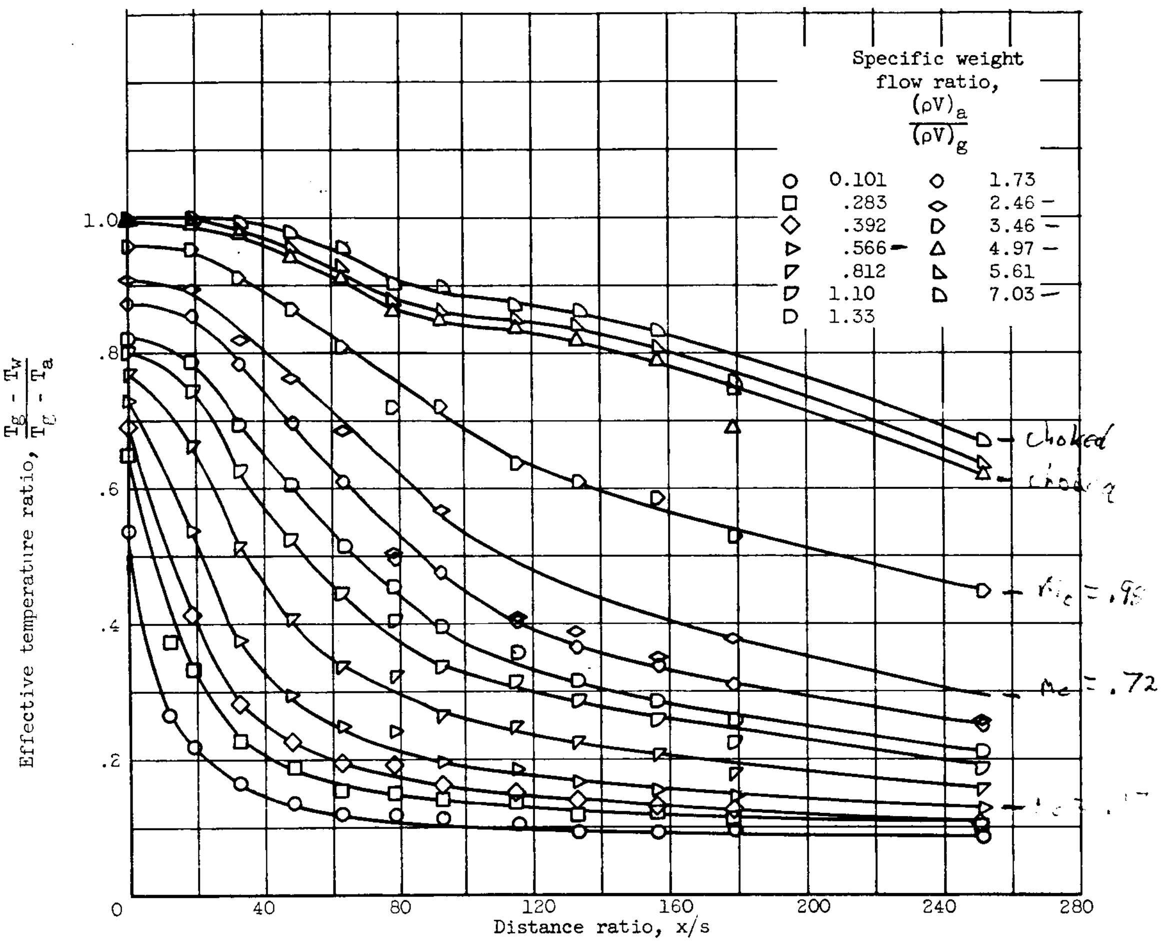


(a) Mainstream gas temperature, 1485° R; slot gas temperature, 550° R; temperature ratio, 2.700; mainstream Mach number, 0.70.

Figure 4. - Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.

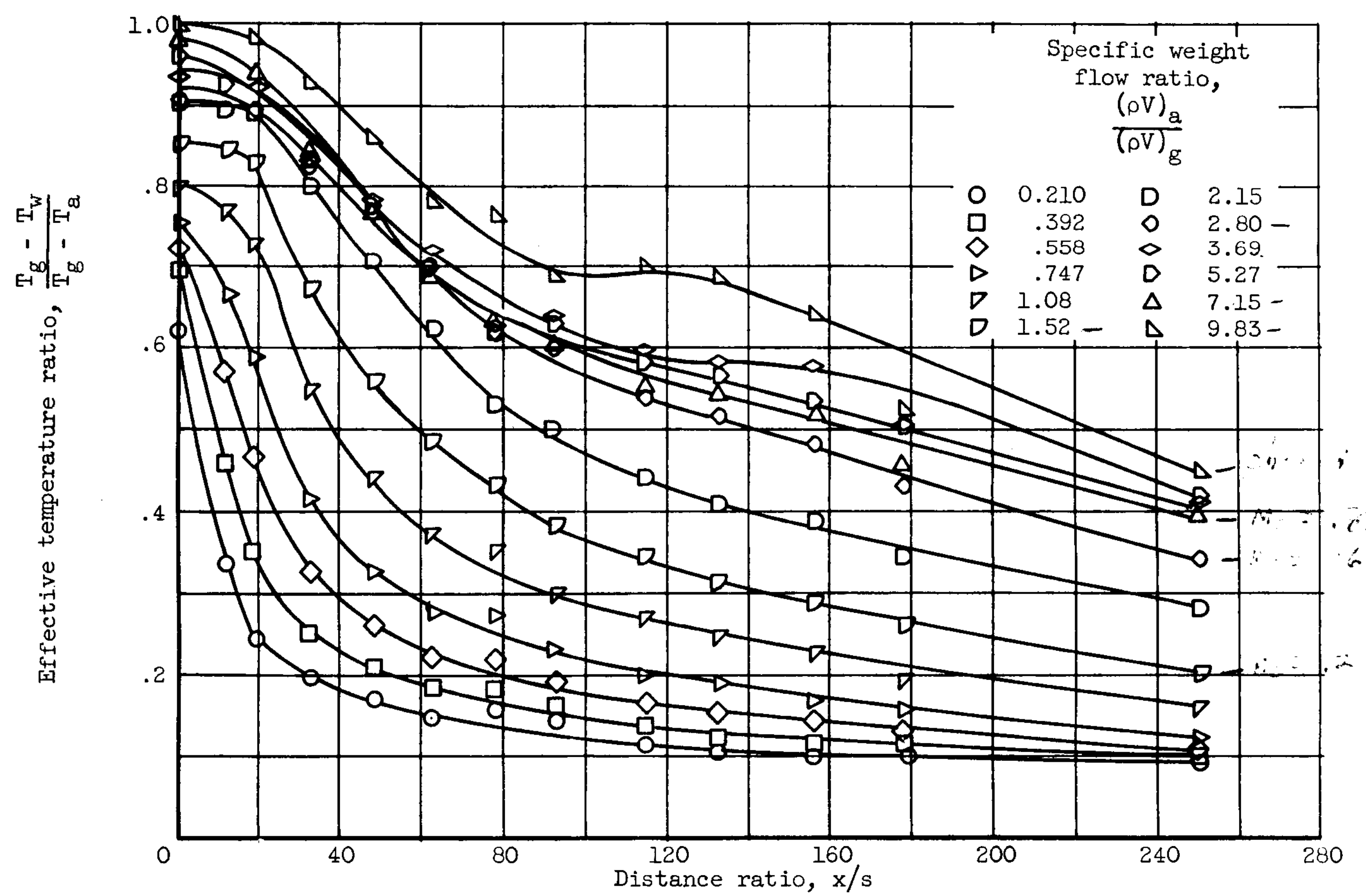
E-212

E-212



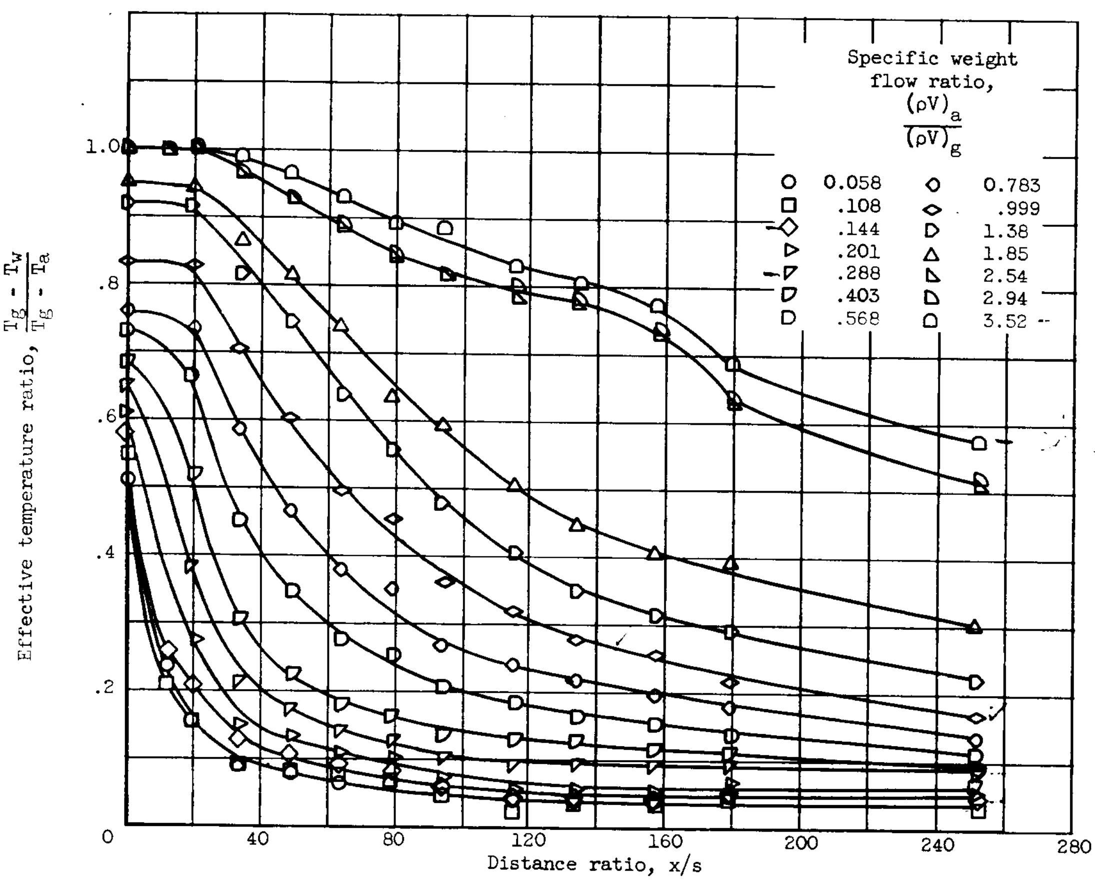
(b) Mainstream gas temperature, 1490° R; slot gas temperature, 545° R; temperature ratio; 2.734; mainstream Mach number, 0.51.

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



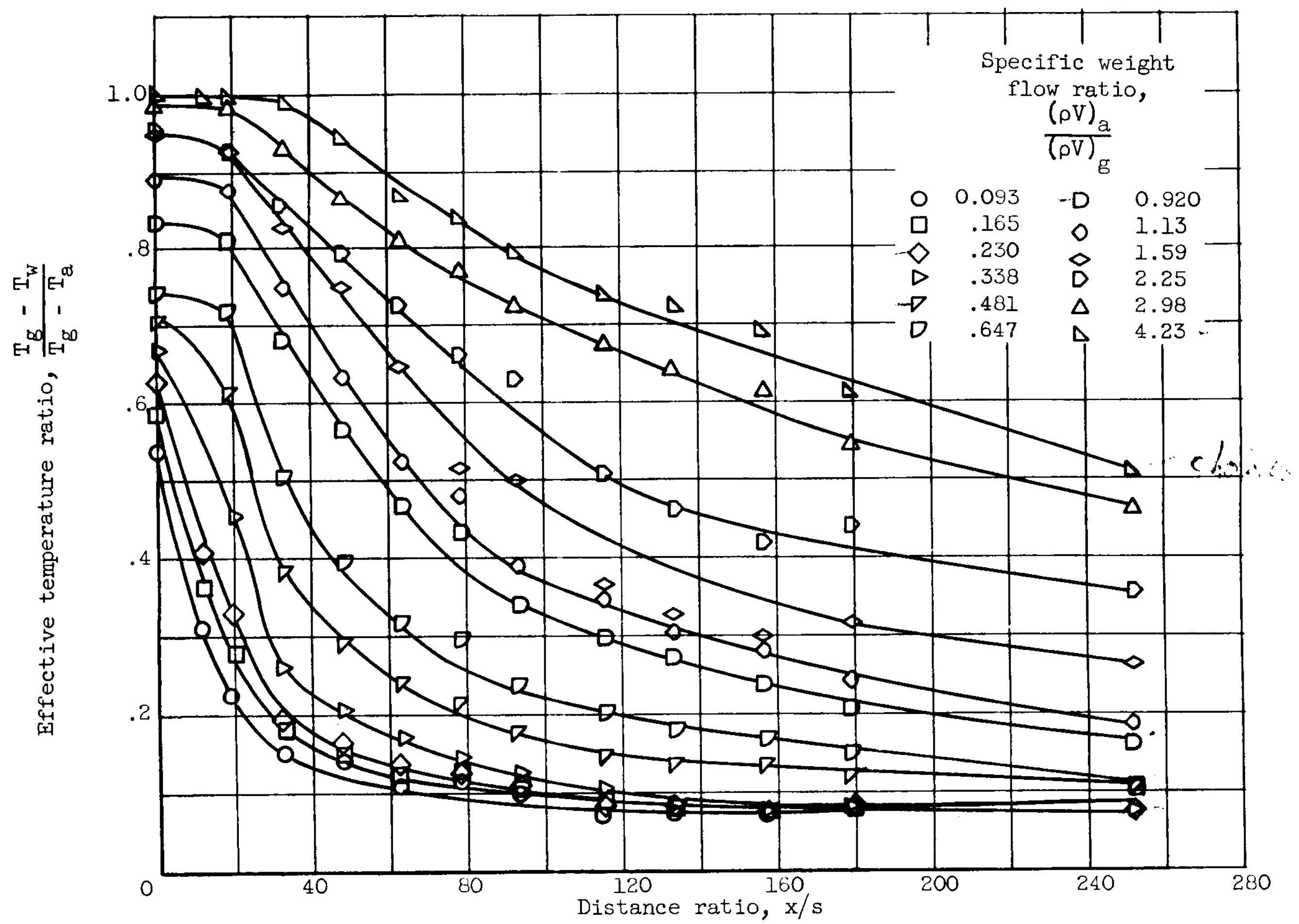
(c) Mainstream gas temperature, 1500° R; slot gas temperature, 545° R; temperature ratio, 2.752; mainstream Mach number, 0.22.

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



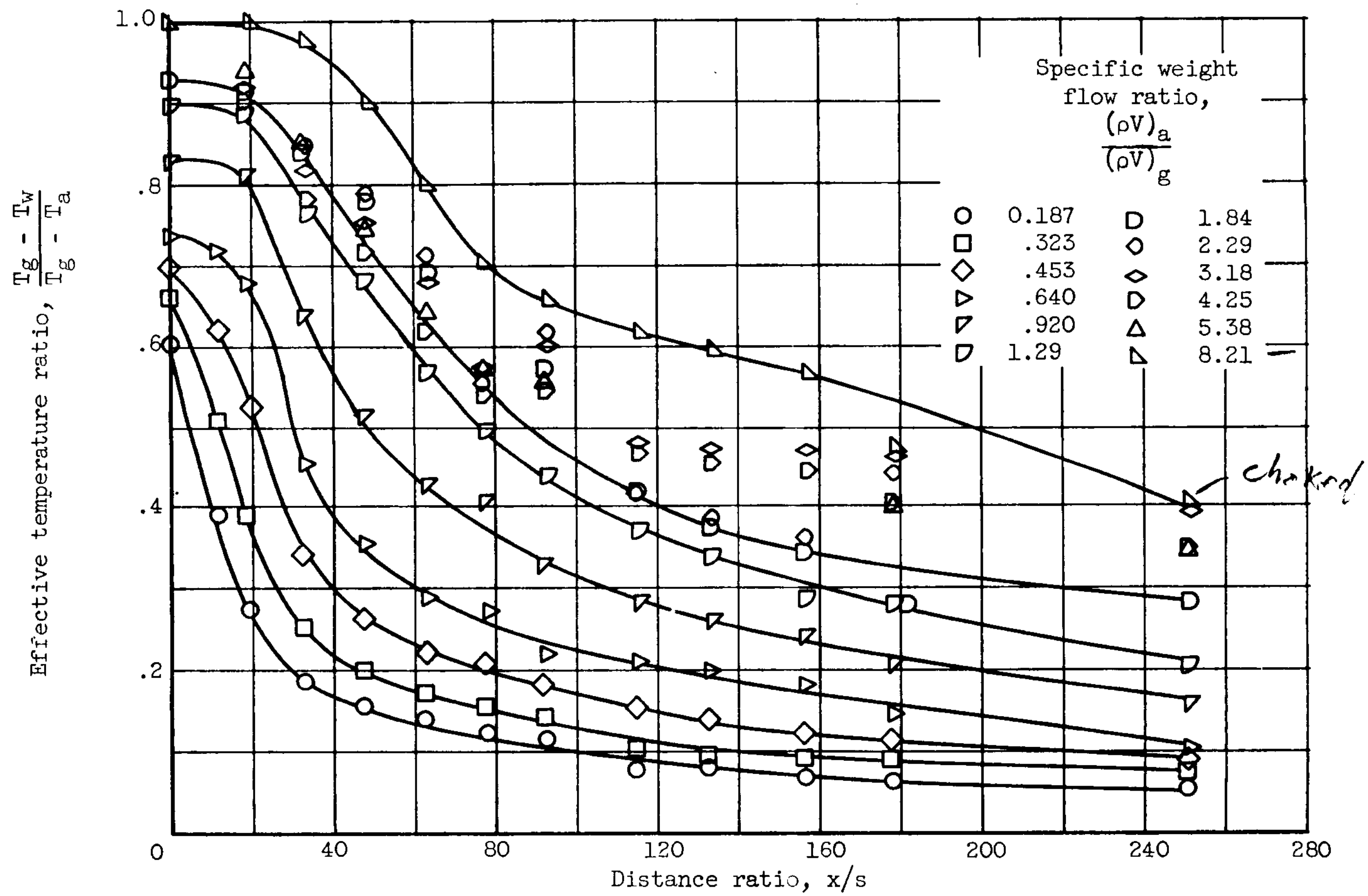
(d) Mainstream gas temperature, 995° R; slot gas temperature, 540° R; temperature ratio, 1.843; mainstream Mach number, 0.70.

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



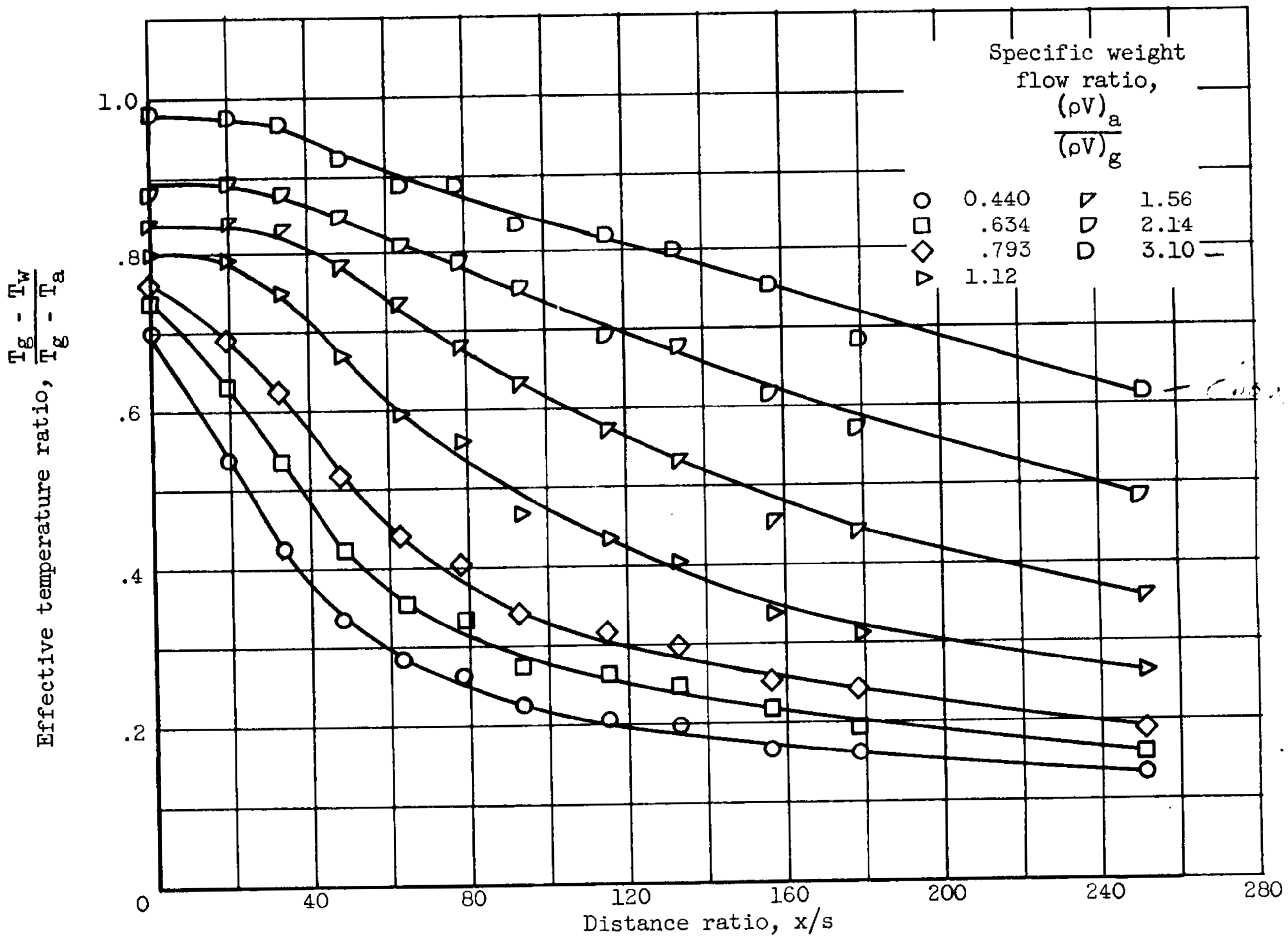
(e) Mainstream gas temperature, 990° R; slot gas temperature, 538° R; temperature ratio, 1.840; mainstream Mach number, 0.50.

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



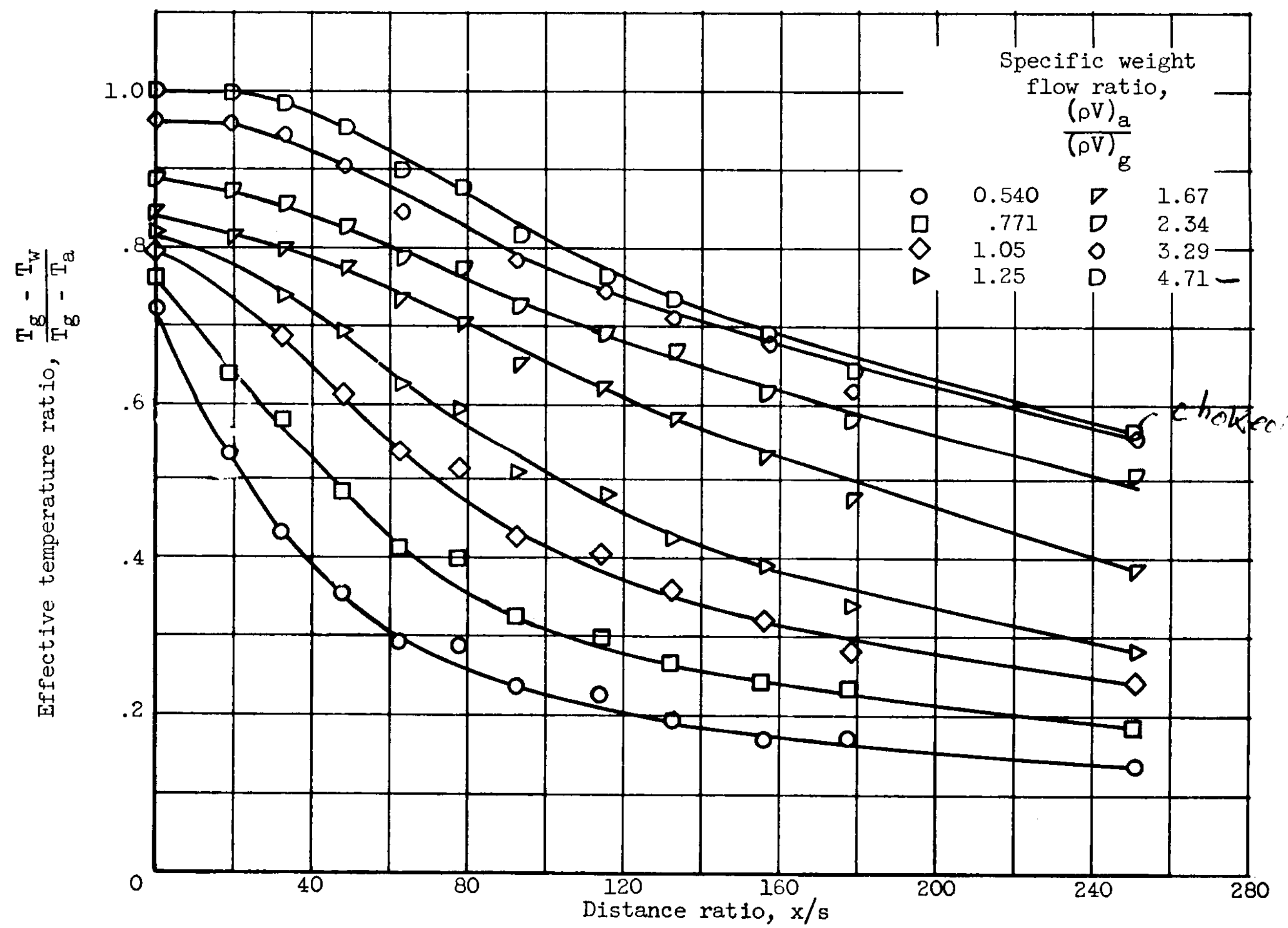
(f) Mainstream gas temperature, 1010° R; slot gas temperature, 536° R; temperature ratio, 1.884; mainstream Mach number, 0.23.

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



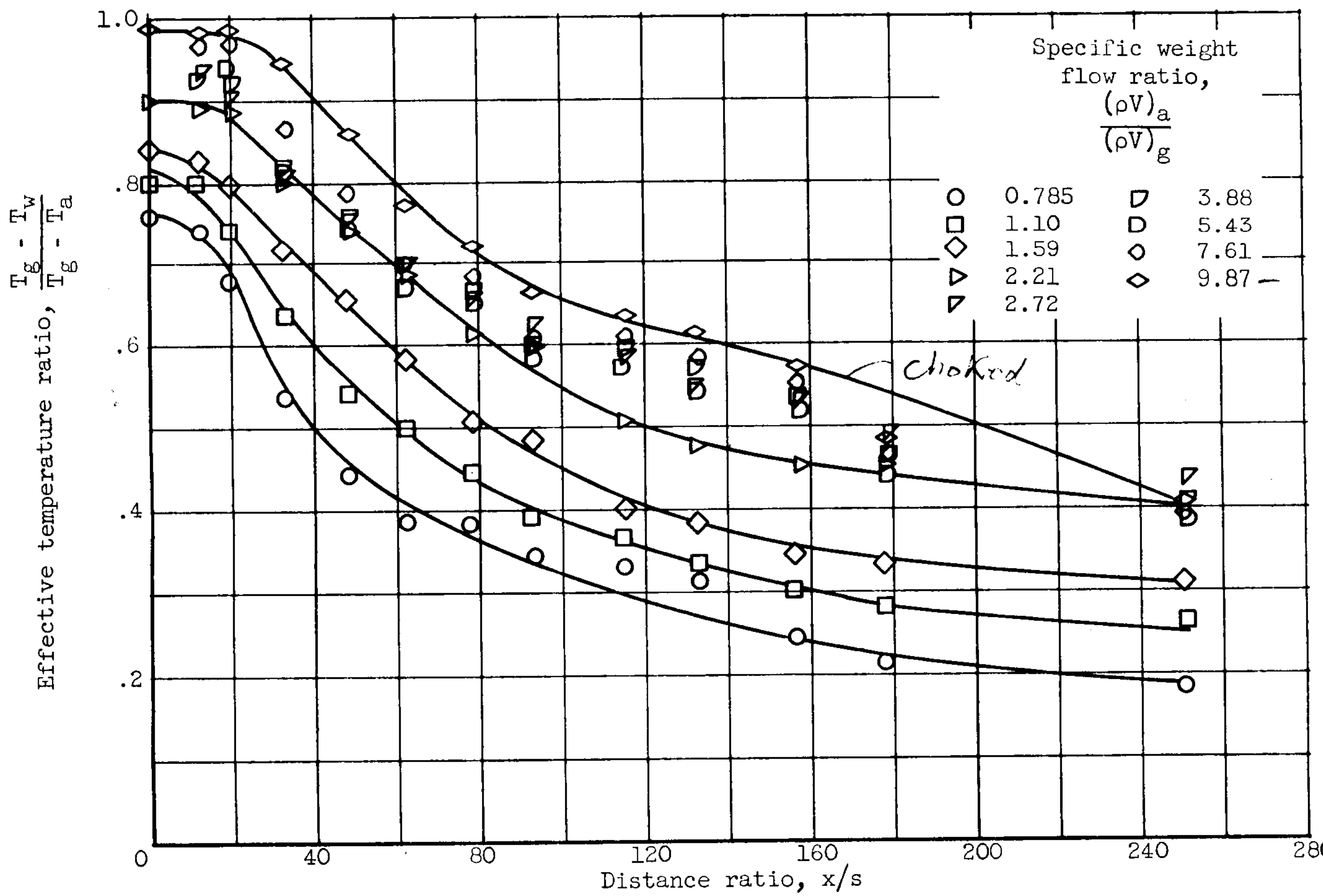
(g) Mainstream gas temperature, 1500° R; slot gas temperature, 875° R; temperature ratio, 1.714; mainstream Mach number, 0.70.

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



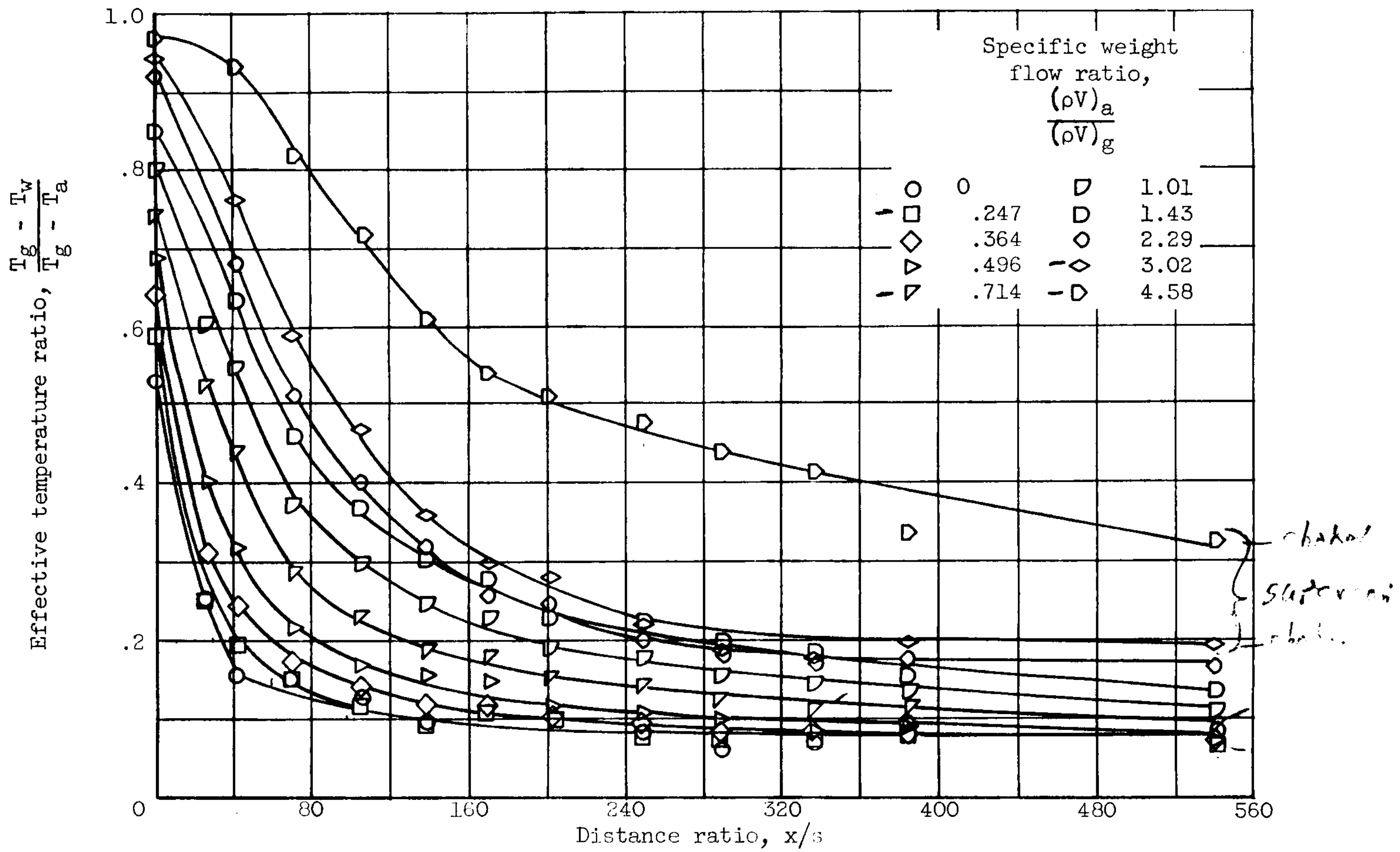
(h) Mainstream gas temperature, 1490° R; slot gas temperature, 875° R; temperature ratio, 1.703; mainstream Mach number, 0.50

Figure 4. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



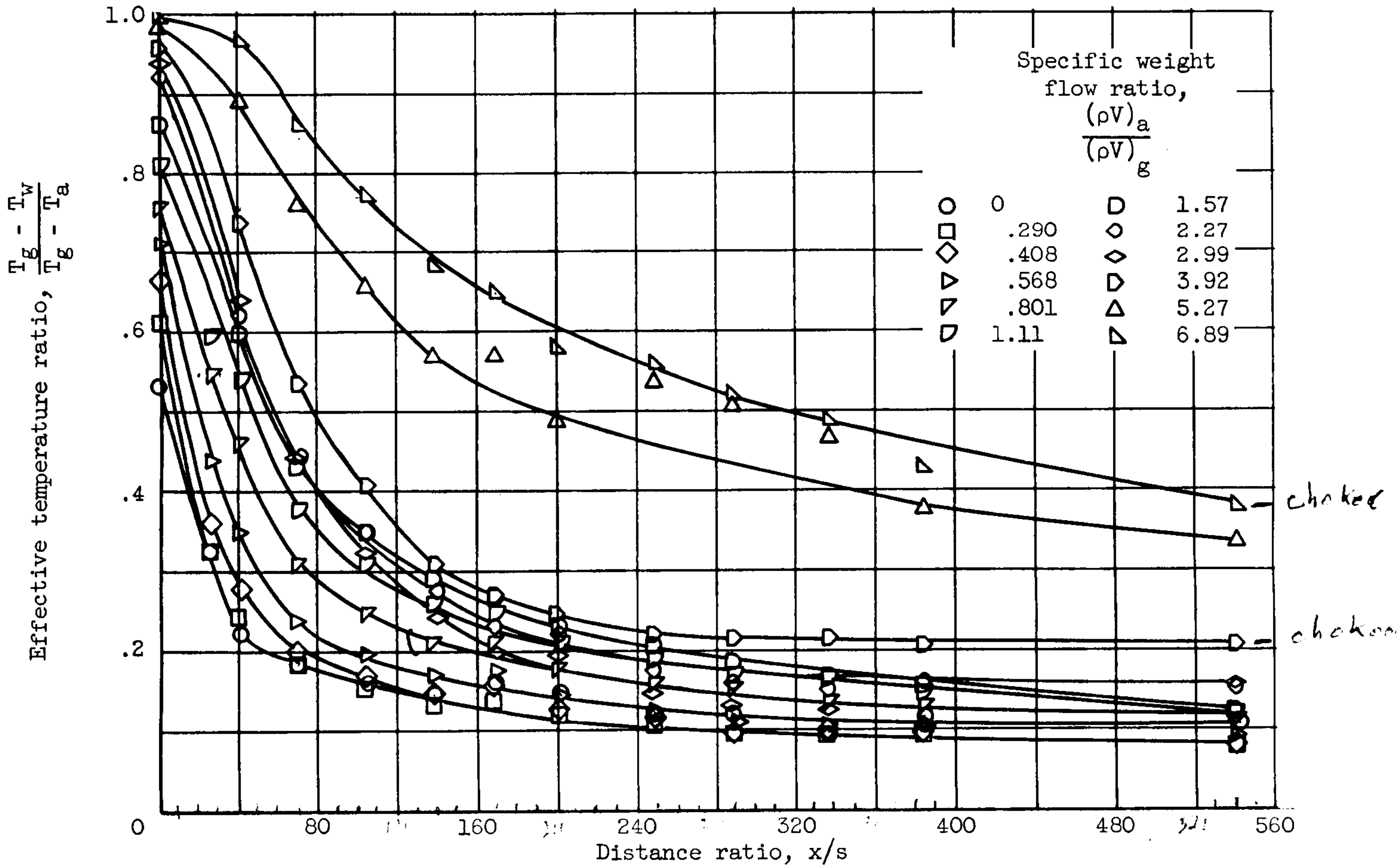
(i) Mainstream gas temperature, 1505° R; slot gas temperature, 880° R; temperature ratio, 1.710; mainstream Mach number, 0.20.

Figure 4. - Concluded. Specific-weight-flow-ratio effect on film cooling at a slot height of one-eighth inch and constant values of mainstream Mach number and temperature ratio.



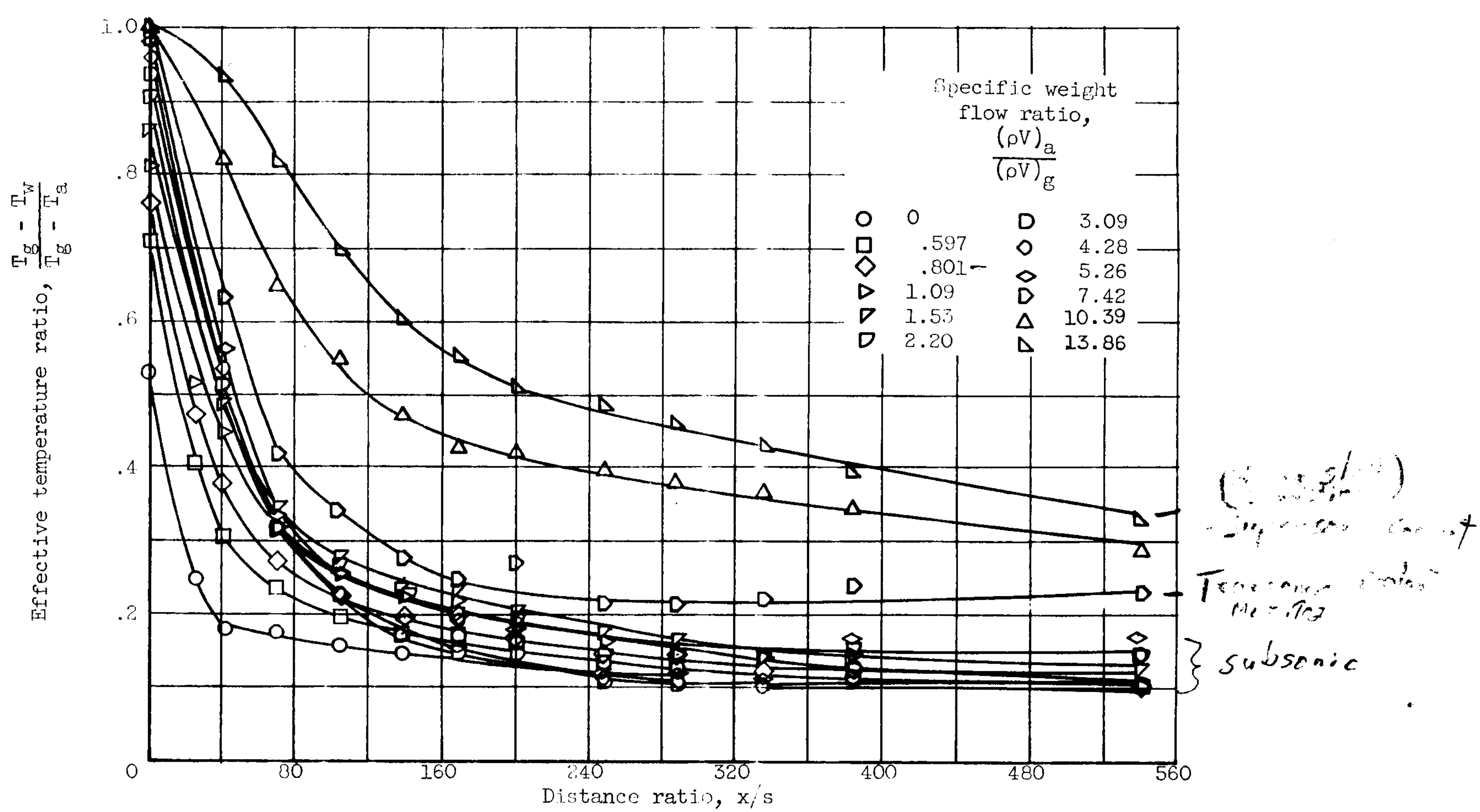
(a) Mainstream gas temperature, 1495° R; slot gas temperature, 557° R; temperature ratio, 2.684; mainstream Mach number, 0.70.

Figure 5. - Specific-weight-flow-ratio effect on film cooling at a slot height of one-sixteenth inch and constant values of mainstream Mach number and temperature ratio.



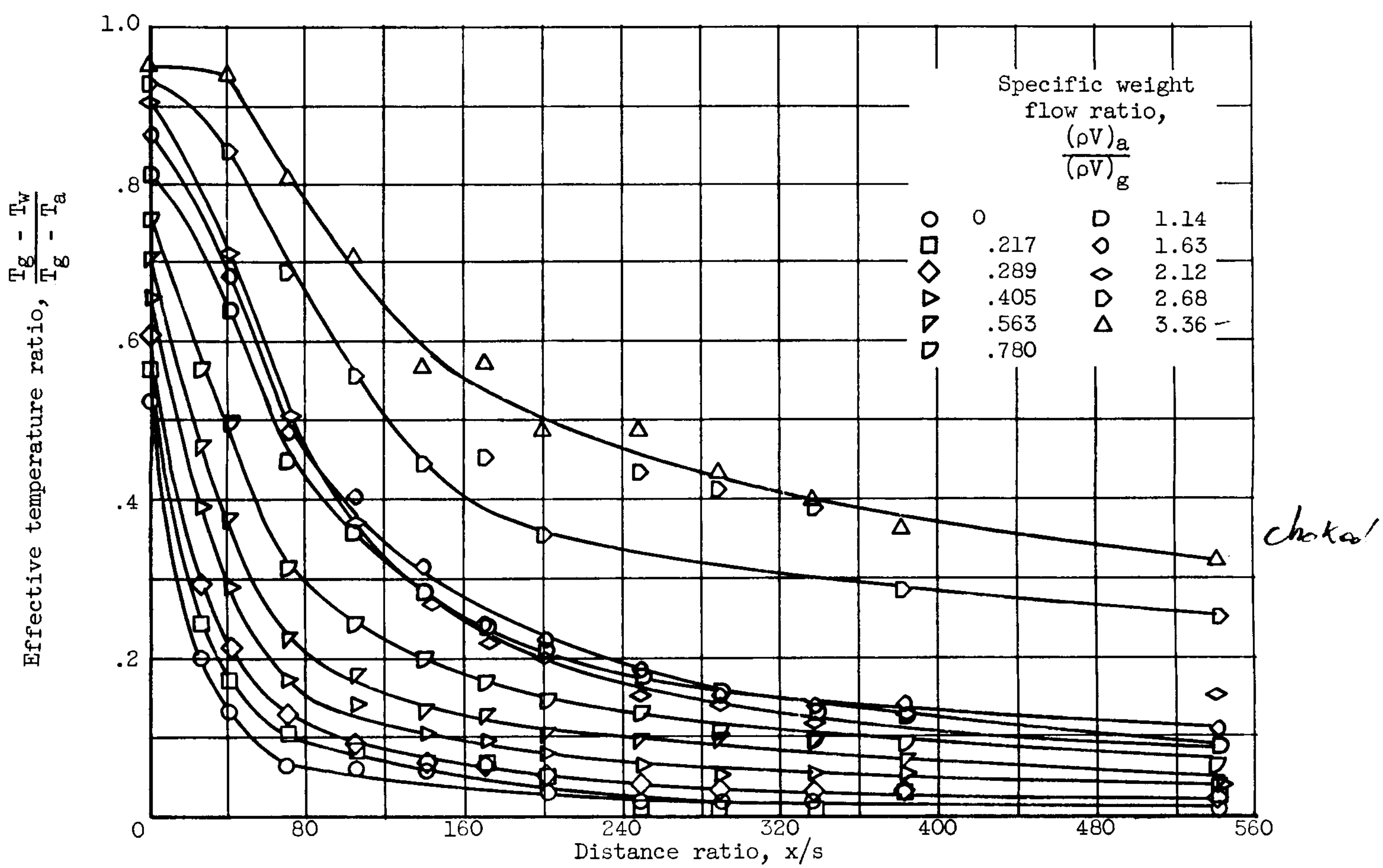
(b) Mainstream gas temperature, 1490° R; slot gas temperature, 550° R; temperature ratio, 2.709; mainstream Mach number, 0.49.

Figure 5. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-sixteenth inch and constant values of mainstream Mach number and temperature ratio.



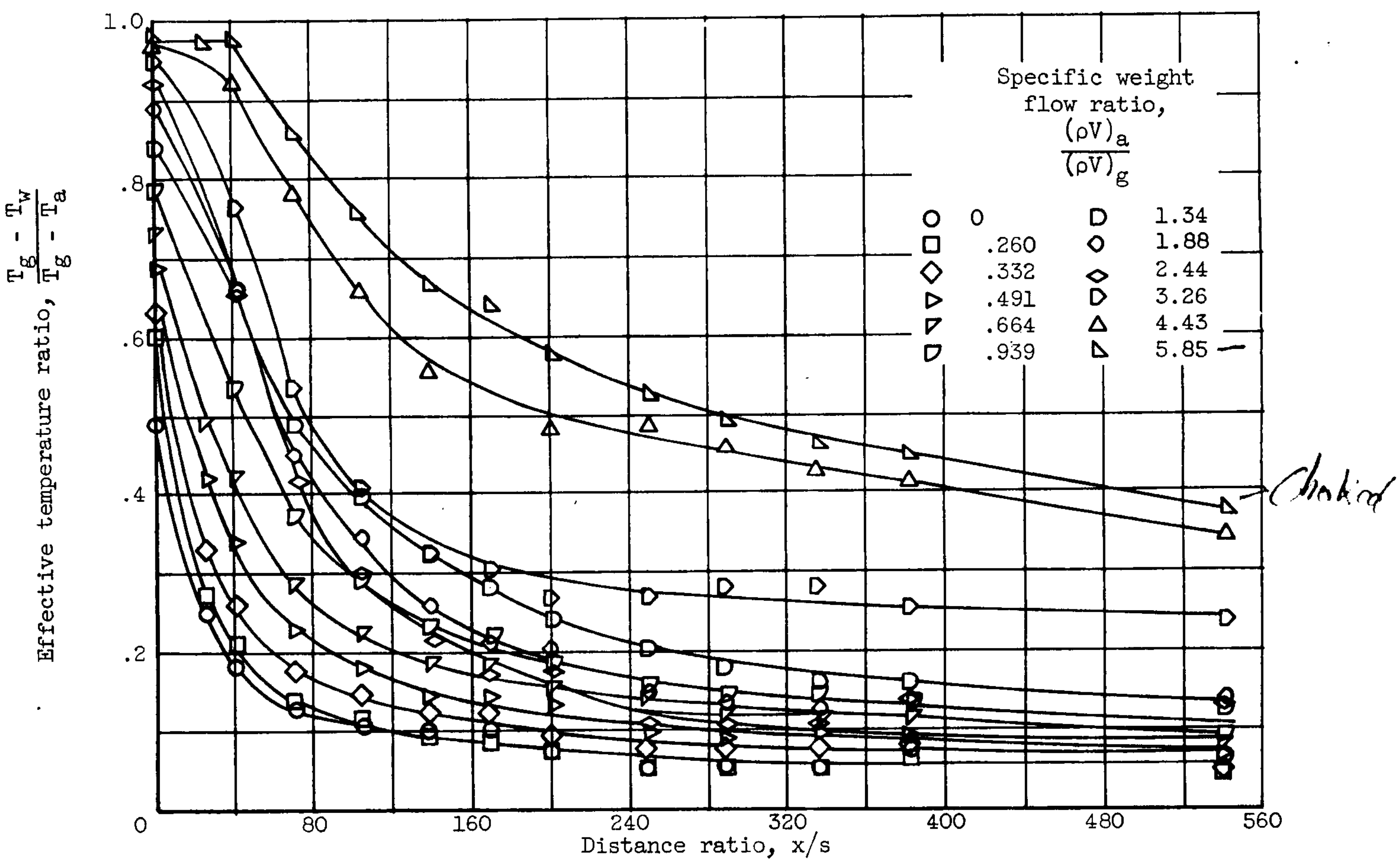
(c) Mainstream gas temperature, 1490° R; slot gas temperature, 548° R; temperature ratio, 2.719; mainstream Mach number, 0.22.

Figure 5. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-sixteenth inch and constant values of mainstream Mach number and temperature ratio.



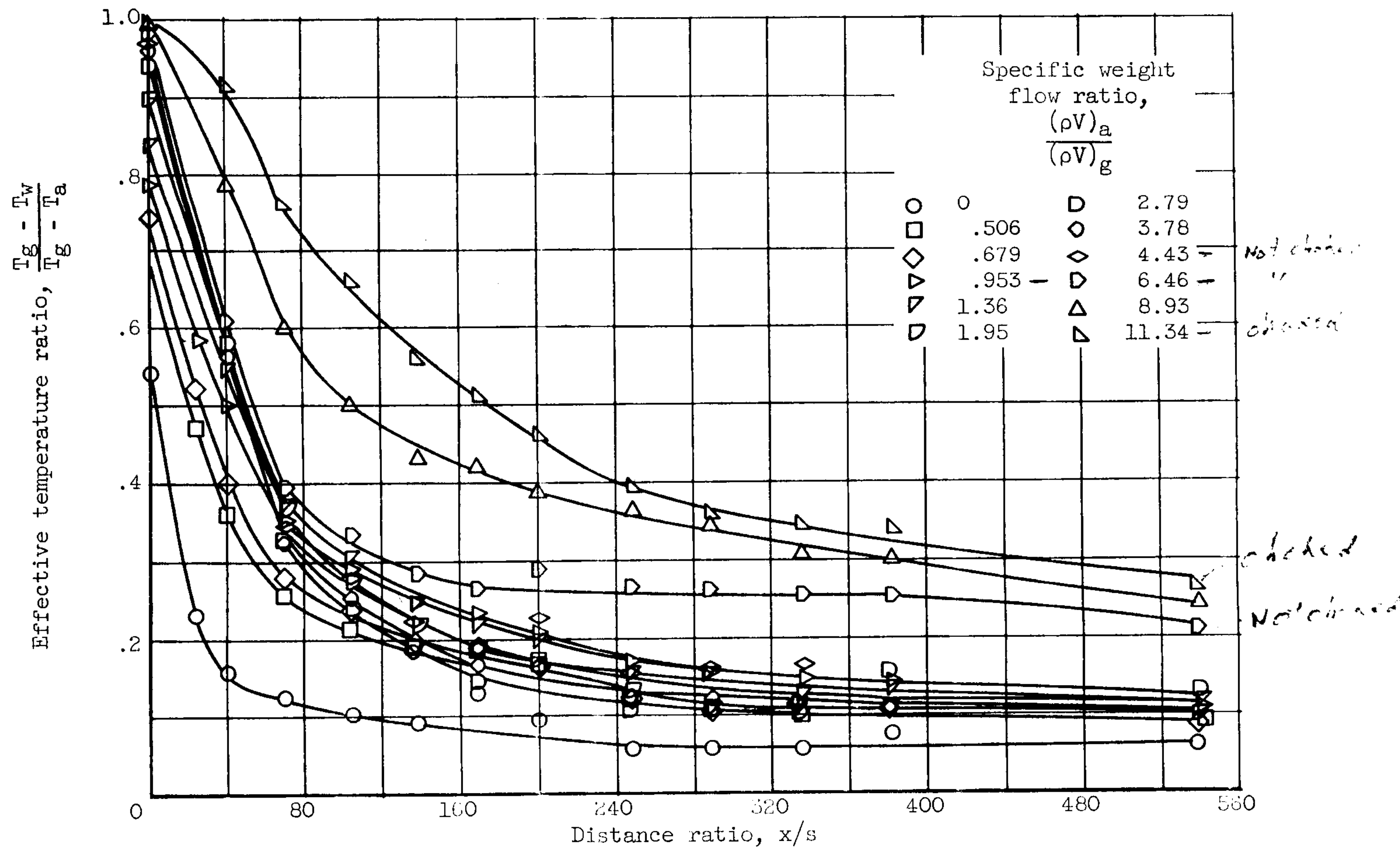
(d) Mainstream gas temperature, 1000° R; slot gas temperature, 544° R; temperature ratio, 1.838; mainstream Mach number, 0.70.

Figure 5. - Continued. Specific-weight-flow-ratio effect on film cooling at a slot height of one-sixteenth inch and constant values of mainstream Mach number and temperature ratio.



(e) Mainstream gas temperature, 1005° R; slot gas temperature, 540° R; temperature ratio, 1.861; mainstream Mach number, 0.50.

Figure 5. - Continued. Specific-wieght-flow-ratio effect on film cooling at a slot height of one-sixteenth inch and constant values of mainstream Mach number and temperature ratio.



(f) Mainstream gas temperature, 1010° R; slot gas temperature, 543° R; temperature ratio, 1.860; mainstream Mach number, 0.20.

Figure 5. - Concluded. Specific-weight-flow-ratio effect on film cooling at a slot height of one-sixteenth inch and constant values of mainstream Mach number and temperature ratio.

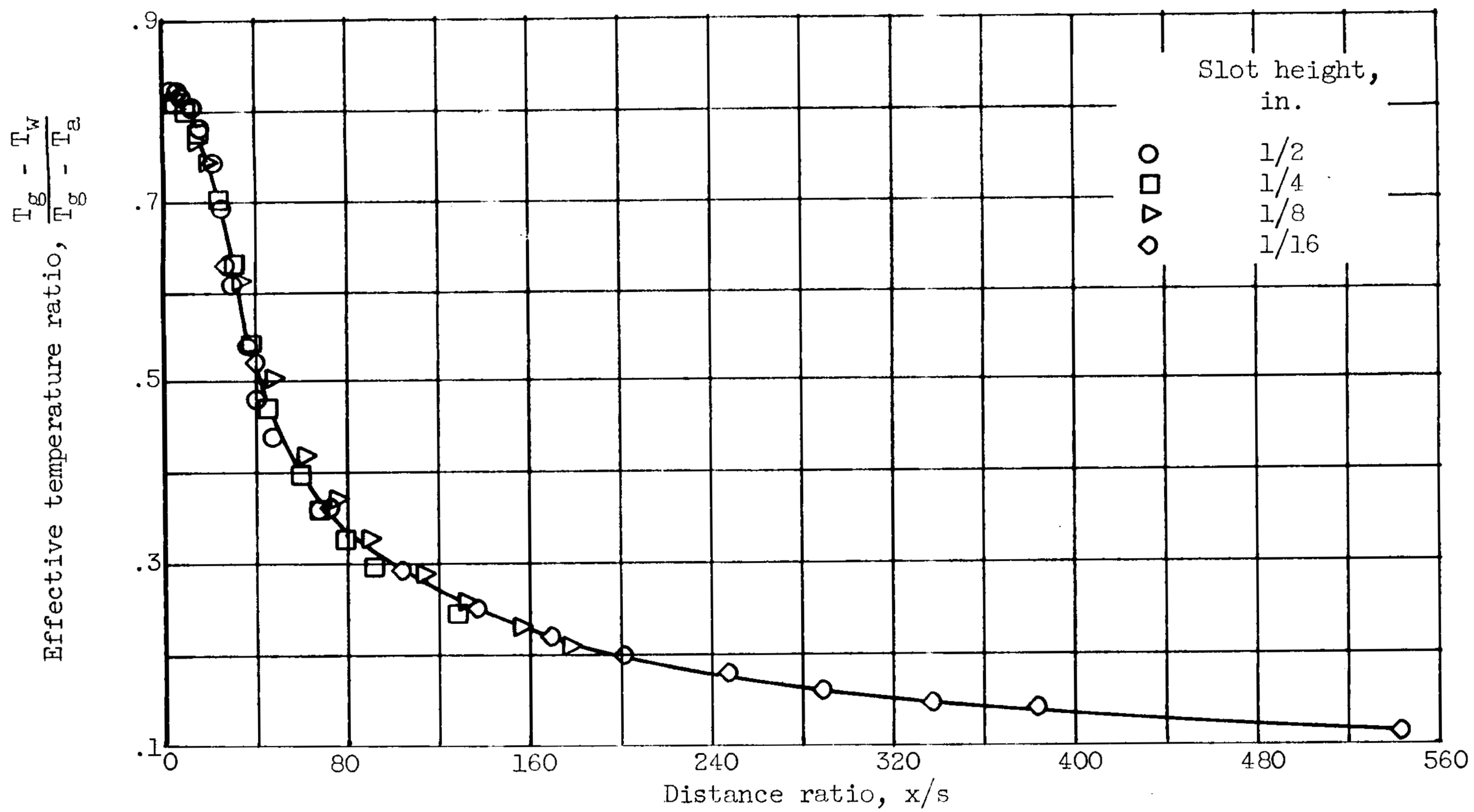


Figure 6. - Slot height effect on film cooling at slot gas temperature of 540° R and mainstream gas temperature of 1500° R and at constant values of temperature ratio of 2.78, mainstream Mach number of 0.50, and specific weight flow ratio of 1.00

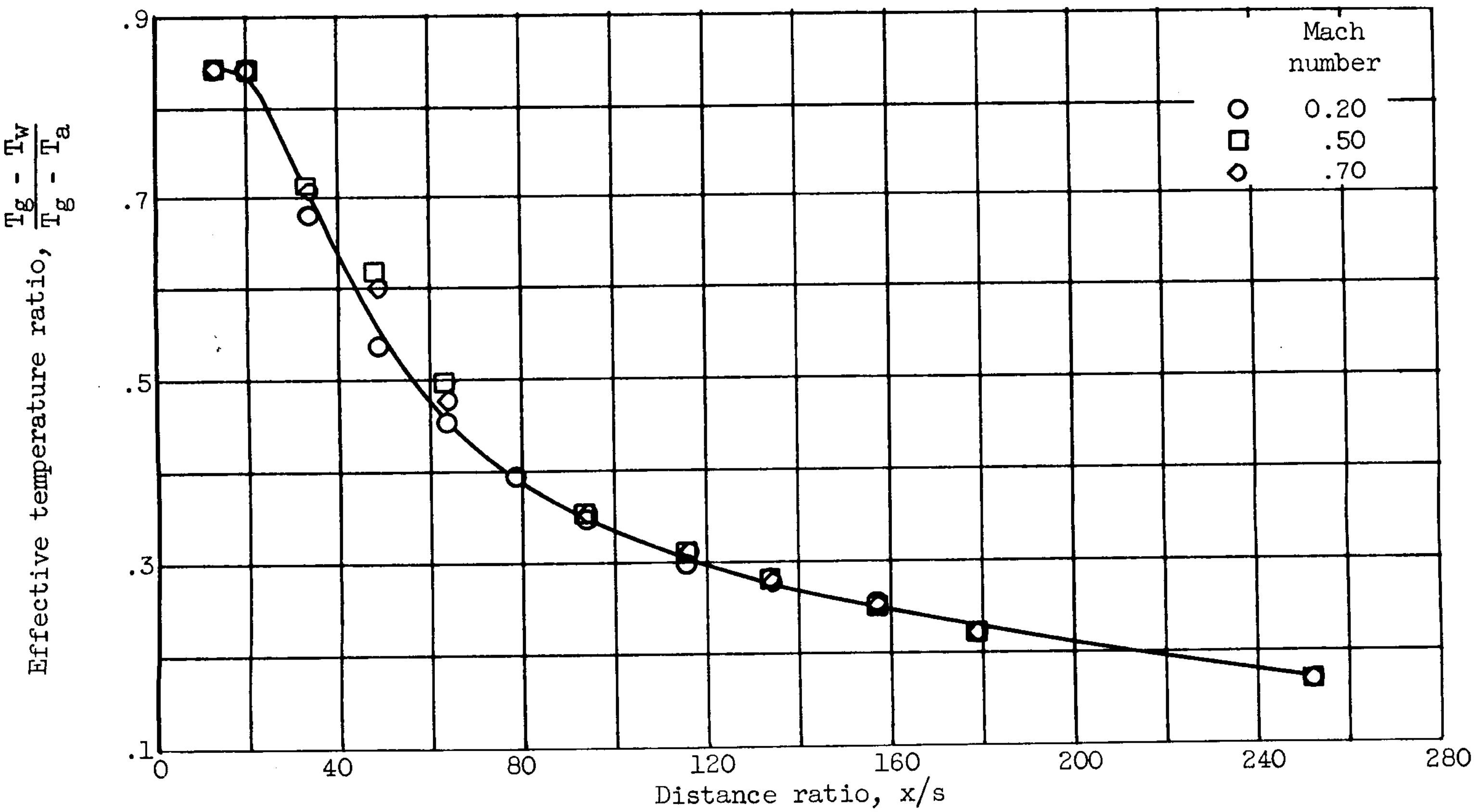


Figure 7. - Mainstream Mach number effect on film cooling at slot gas temperature of 540° R and mainstream gas temperature of 1000° R and at constant values of temperature ratio of 1.85, slot height of one-eighth inch, and specific weight flow ratio of 1.00.

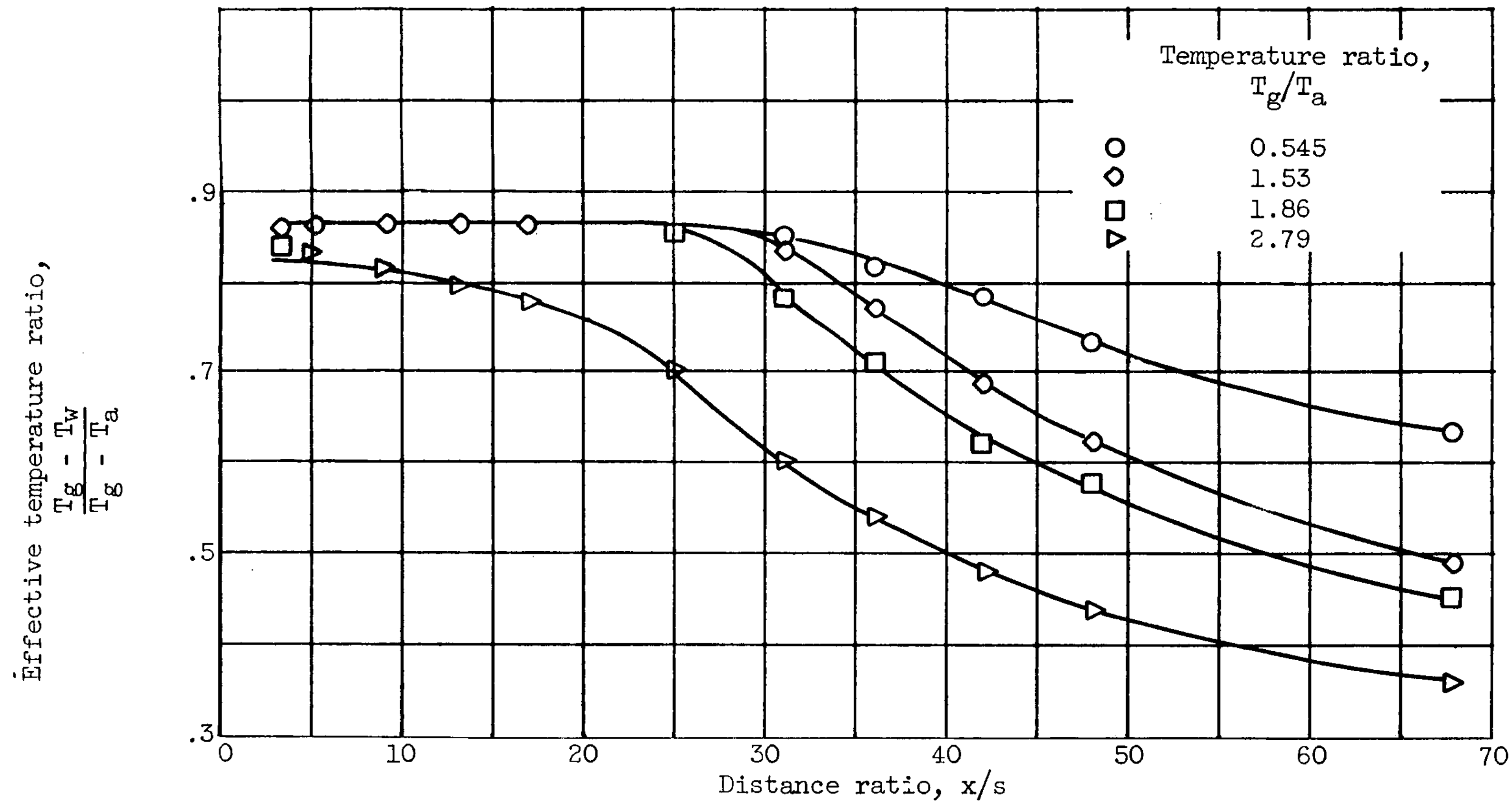


Figure 8. - Temperature-ratio effect on film cooling at constant values of mainstream Mach number of 0.5, slot height of one-half inch, and specific weight flow ratio of 1.00.

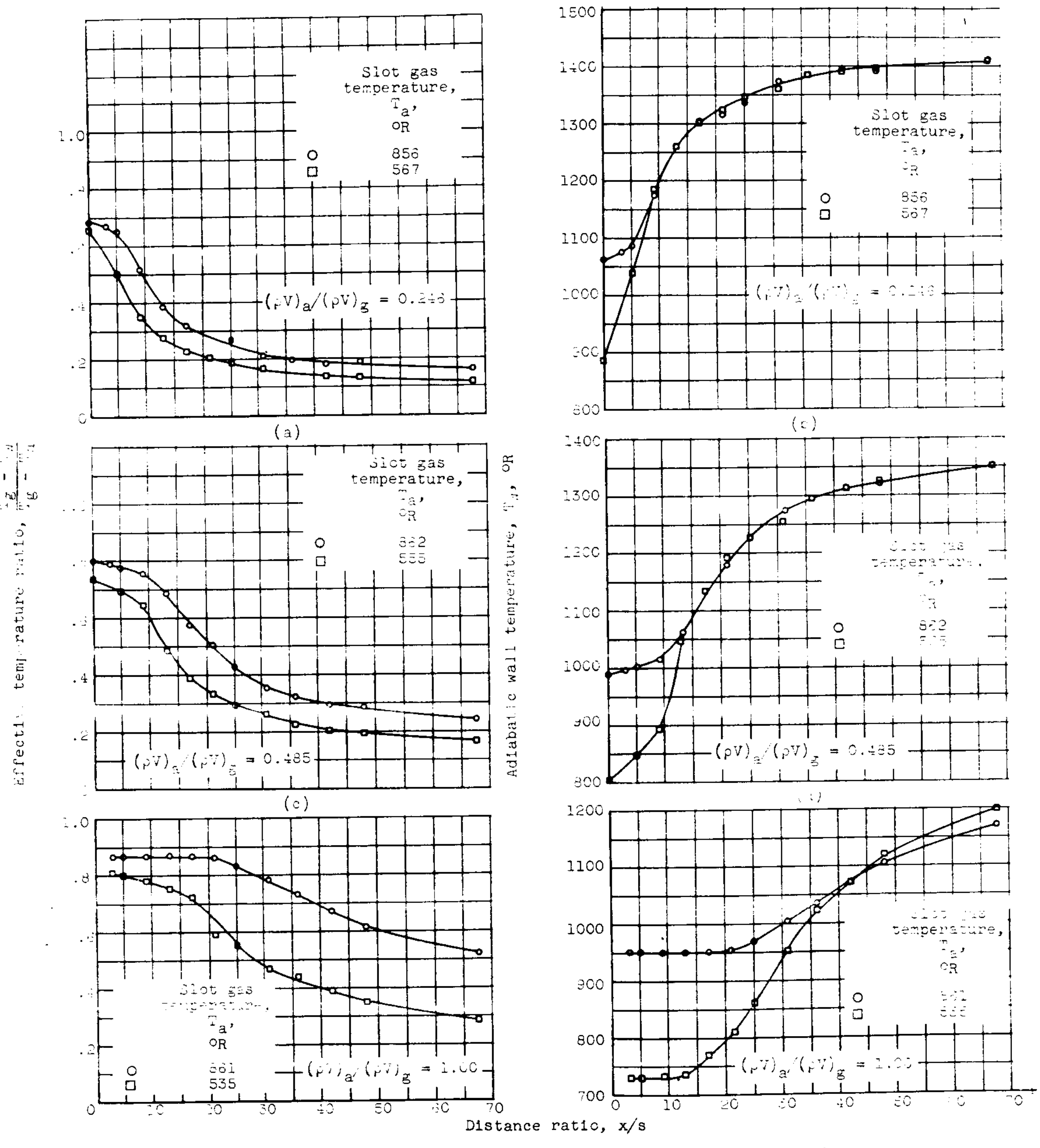


Figure 9. - Effect of cooling-air temperature level on effective temperature ratio and wall temperature at constant value of mainstream gas Mach number of 0.23, slot height of one-half inch, and mainstream gas temperature of 1510° R.

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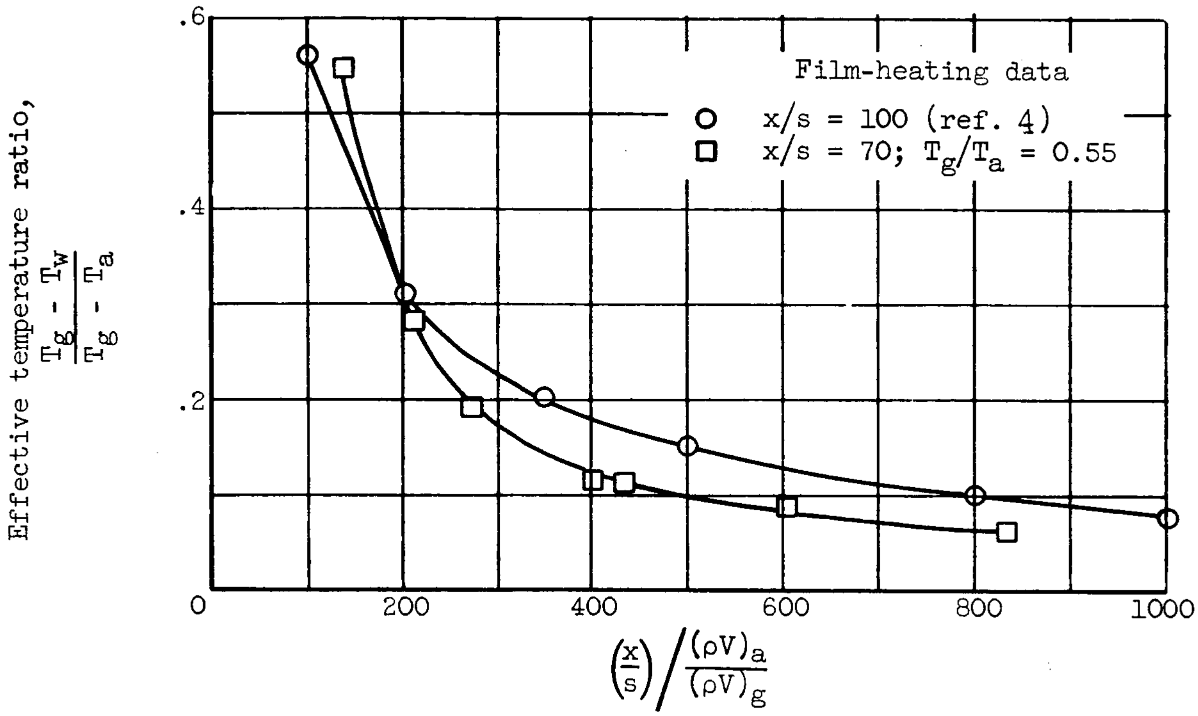


Figure 10. - Comparison between present film-heating data and published data.

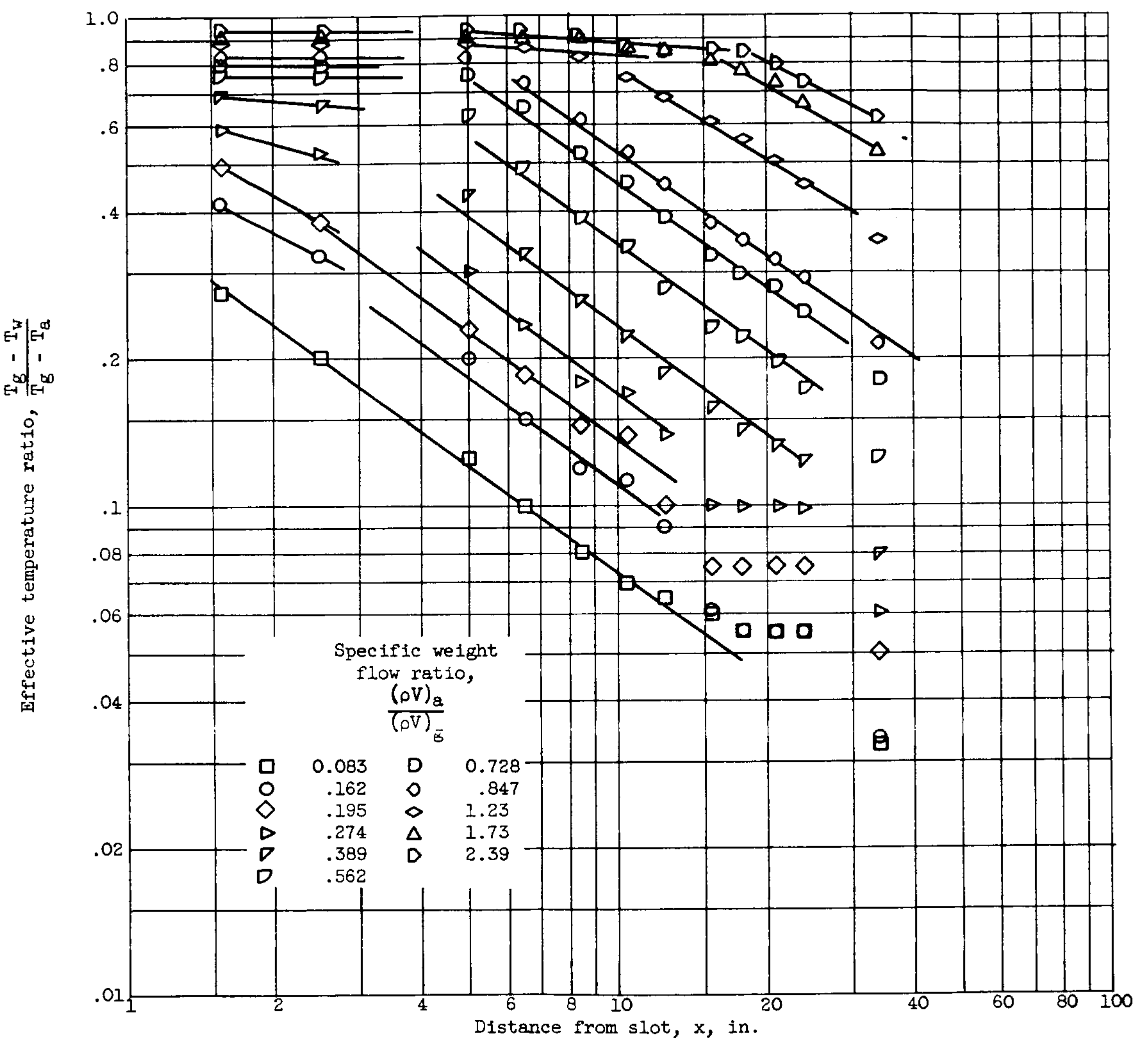


Figure 11. - Determination of exponents to be applied to the (x/s) parameter. Slot gas temperature, 540° R; mainstream gas temperature, 990° R; temperature ratio, 1.833; mainstream Mach number, 0.23; slot height, one-fourth inch.

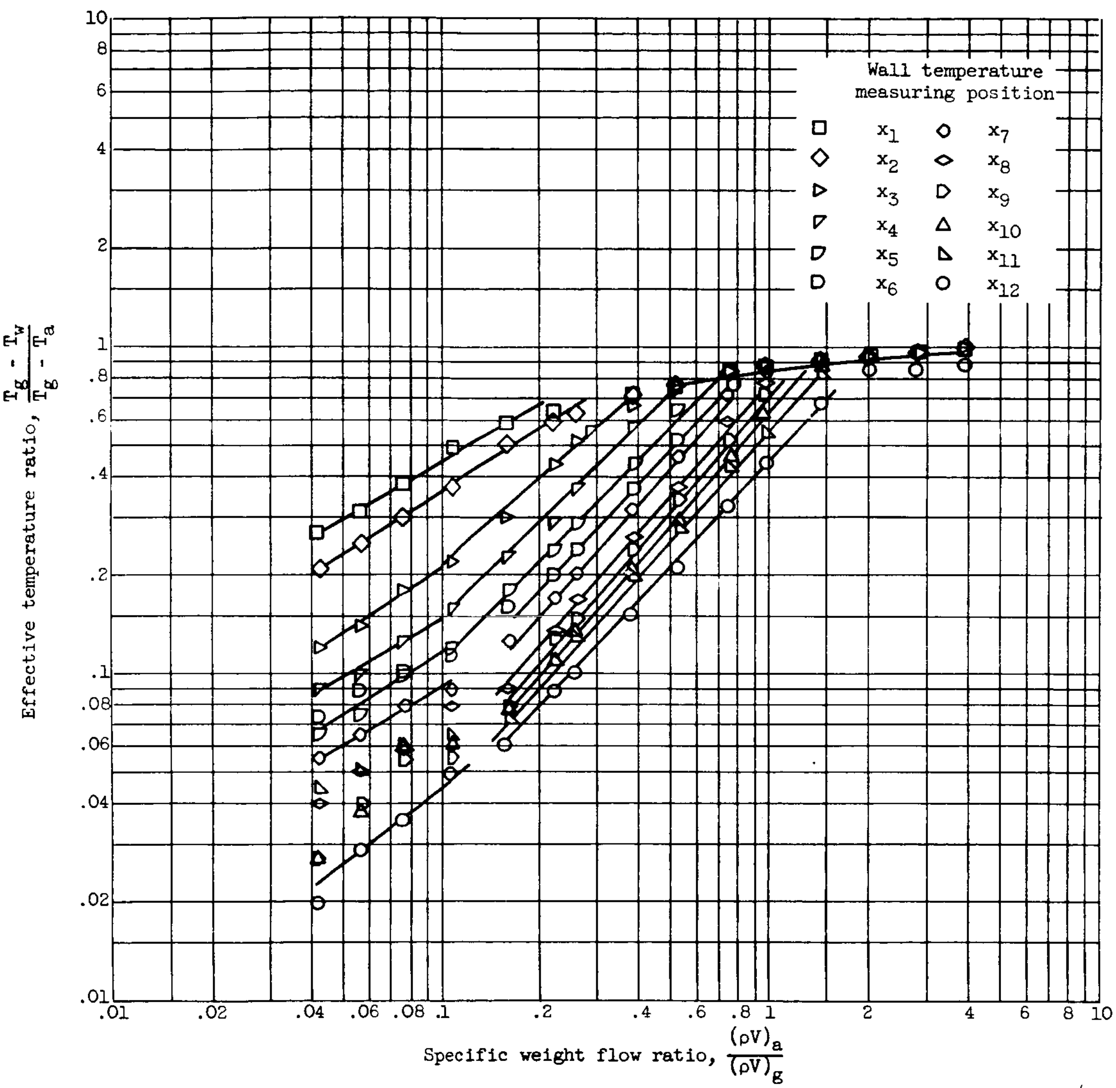


Figure 12. - Determination of exponents to be applied to the specific weight-flow-ratio parameter. Slot gas temperature, 538° R; mainstream gas temperature, 1000° R; temperature ratio, 1.86; mainstream Mach number, 0.53; slot height, one-half inch.

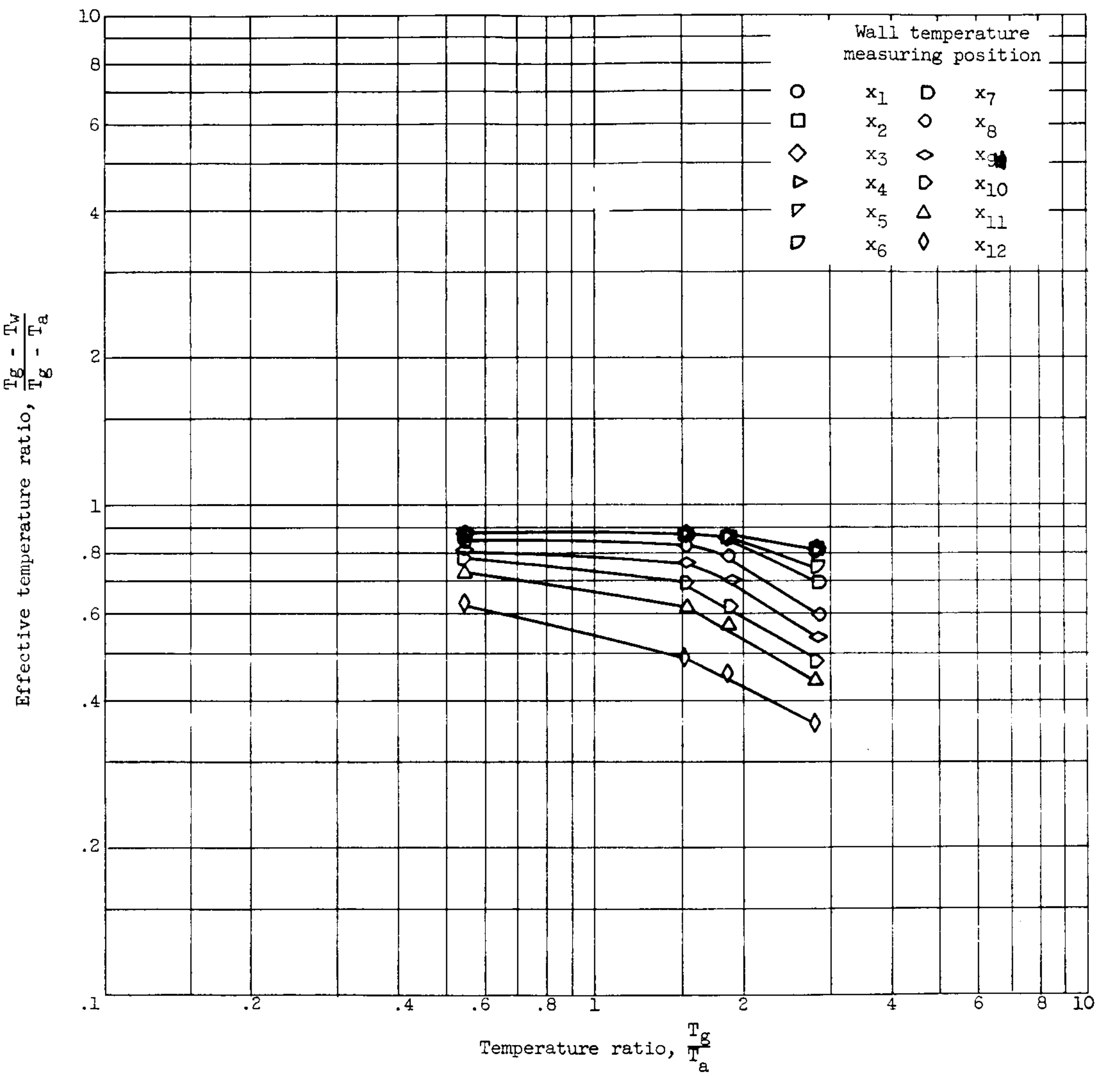
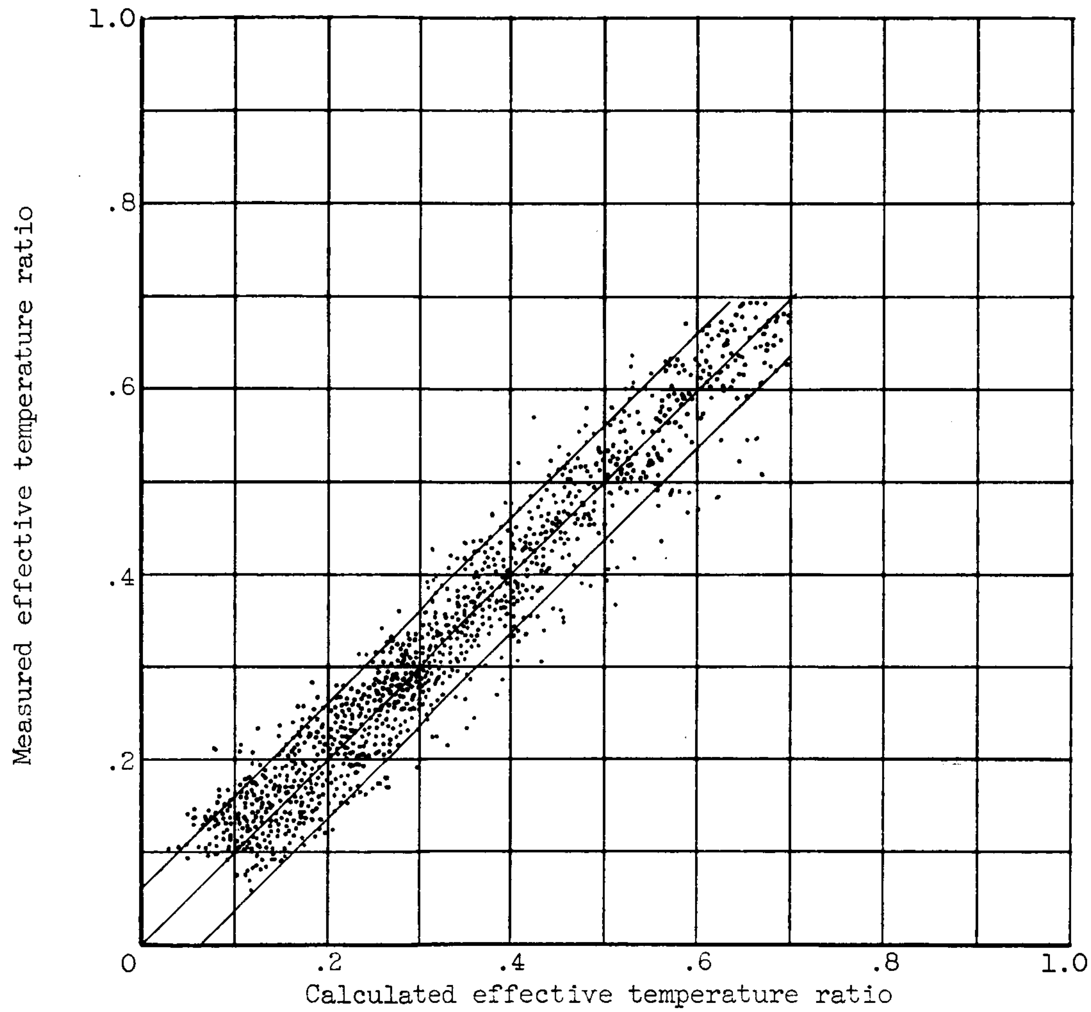


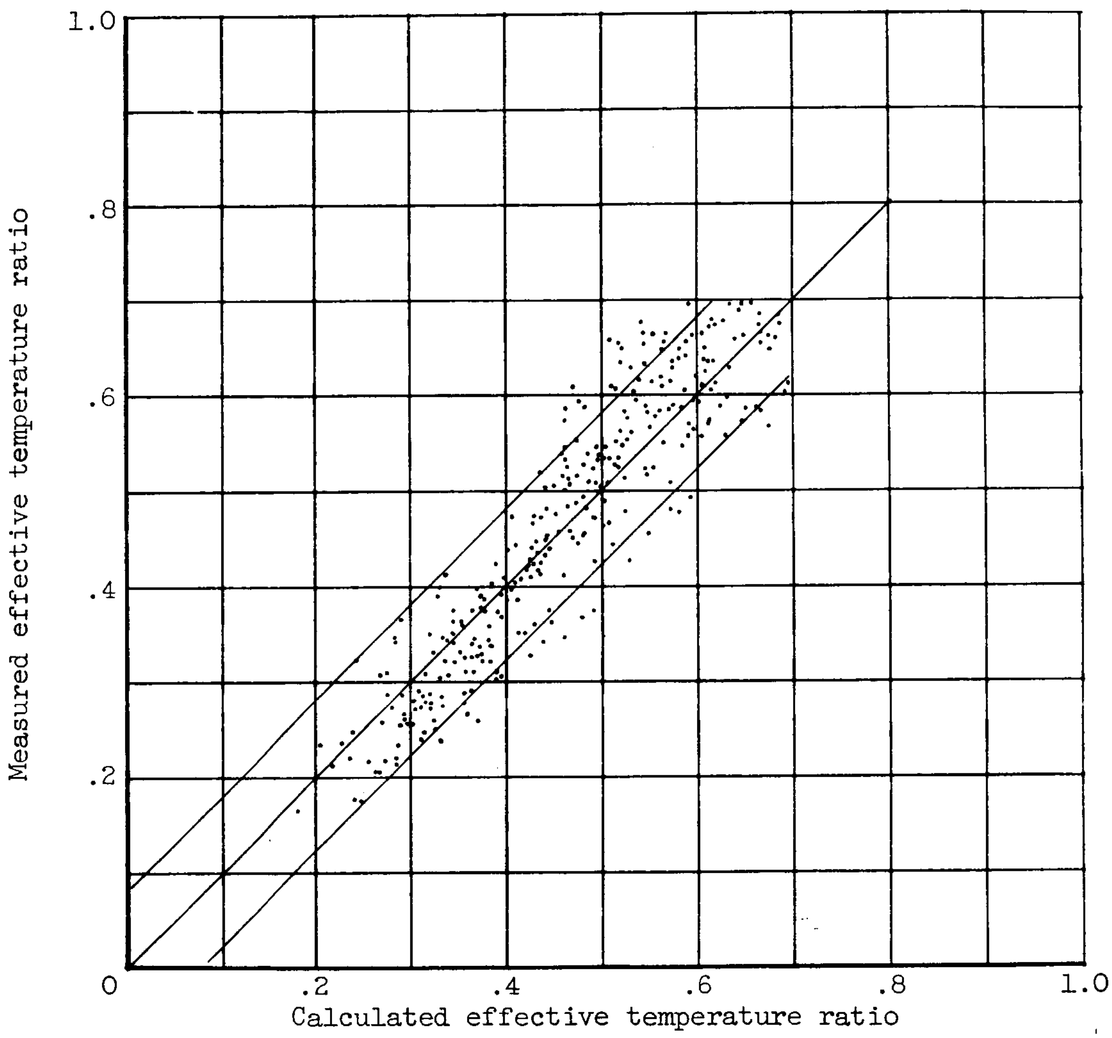
Figure 13. - Determination of exponents to be applied to the temperature-ratio parameter. Mainstream Mach number, 0.5; slot height, one-half inch; specific weight flow ratio, 1.00.

E-212



(a) $\frac{T_g - T_w}{T_g - T_a} = 12.6 \left[\frac{(\rho V)_a}{(\rho V)_g}\right] \left(\frac{s}{x}\right)^{0.72} \left(\frac{T_a}{T_g}\right)^{0.50} < 0.70$; restrictions on equation: 92.2 percent of data included within ± 0.06 band, $(\rho V)_a/(\rho V)_g \lessapprox 2.0$, s, 1/16 to 1/2 inch, $x > 3.5$ inches.

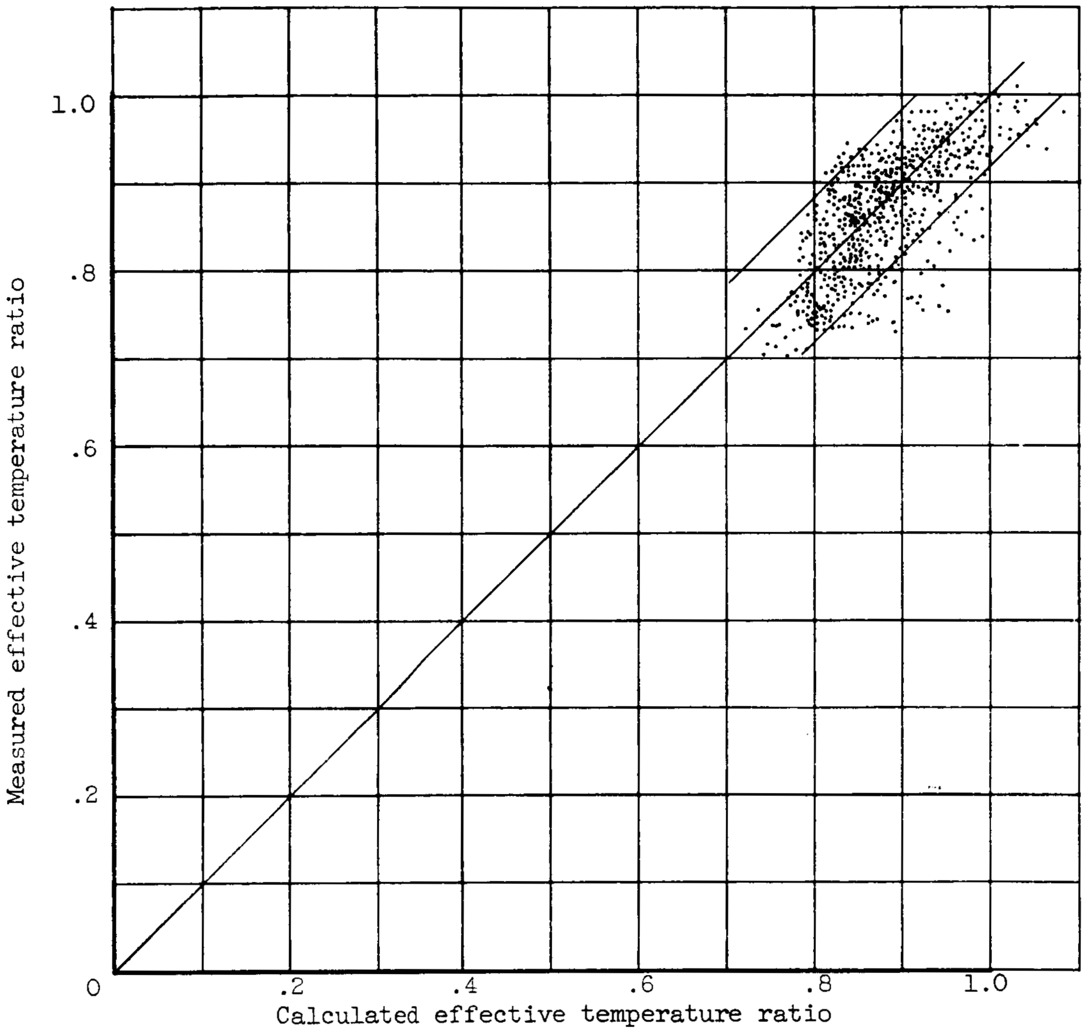
Figure 14. - Correlation results.



(b) $\frac{T_g - T_w}{T_g - T_a} = 1.86 \left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.44} \left(\frac{s}{x}\right)^{0.36} < 0.70$; restrictions on equation: 87 percent of data included within ±0.08 band, $(\rho V)_a/(\rho V)_g \lesssim 2.0$, s, 1/16 to 1/2 inch, x < 3.5 inch.

Figure 14. - Continued. Correlation results.

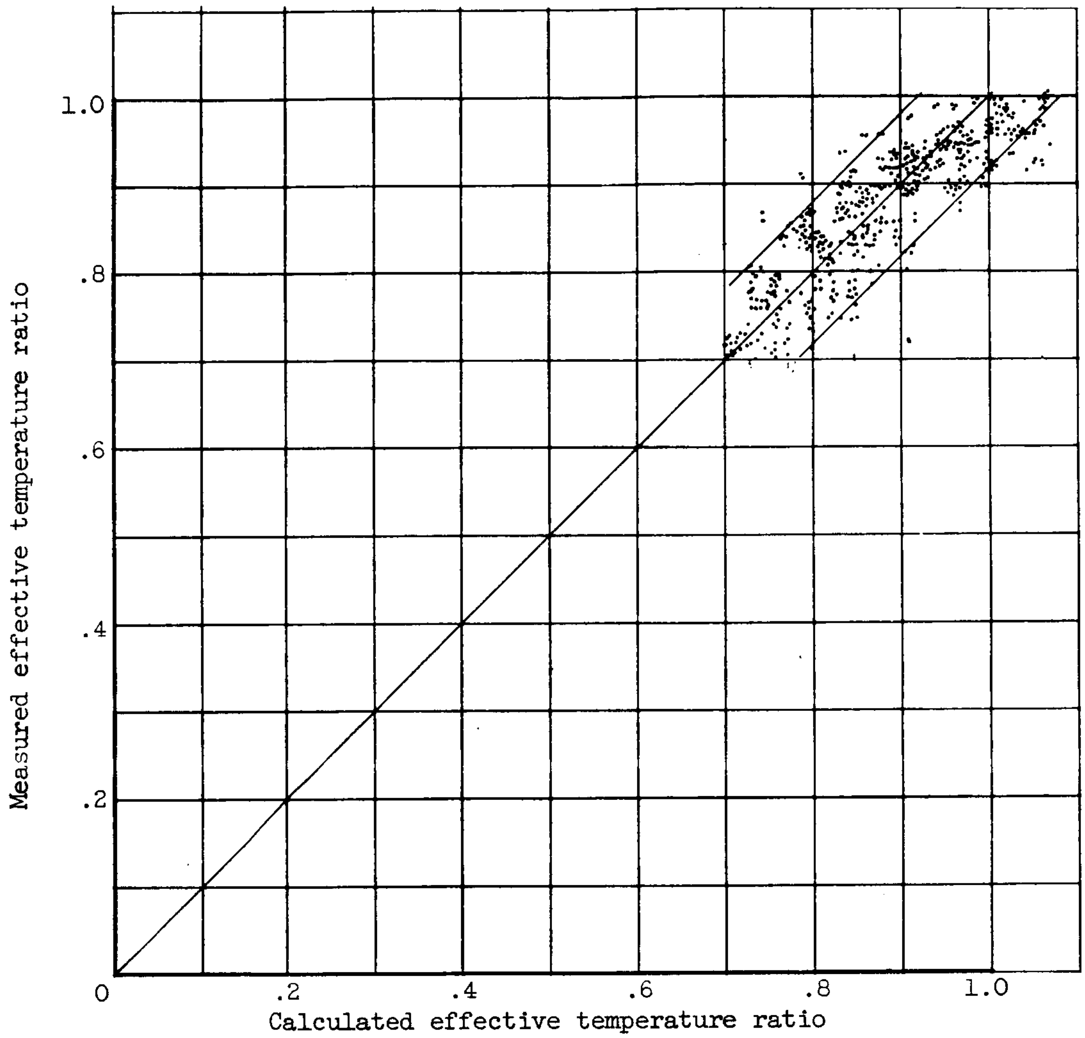
E-212



(c) $\frac{T_g - T_w}{T_g - T_a} = 1.15 \left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.18} \left(\frac{s}{x}\right)^{0.11} > 0.70$; restrictions on equation: 89.3 percent of data included in ±0.08 band, $(\rho V)_a/(\rho V)_g < 4.0$, s, 1/8 to 1/2 inch, $x/s > 18.6$.

Figure 14. - Continued. Correlation results.

E-212



(d) $\frac{T_g - T_w}{T_g - T_a} = 0.83 \left[\frac{(\rho V)_a}{(\rho V)_g}\right]^{0.18} > 0.70$; restrictions on equation: 93.7 percent of data included in ± 0.08 band, $(\rho V)_a/(\rho V)_g < 4.0$, s, 1/8 to 1/2 inch, $x/s < 18.6$.

Figure 14. - Concluded. Correlation results.